Tampere University

Riku Korhonen

SUBSYNCHRONOUS OSCILLATIONS IN WIND POWER PLANTS AND SERIES COMPENSATION IN FINLAND

Master of Science Thesis
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Examiner: Professor Sami Repo
Examiner: Tuomas Rauhala
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ABSTRACT

Riku Korhonen: Subsynchronous oscillations in wind power plants and series compensation in Finland
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The series compensation has been used at the main power transfer routes between northern and southern Finland, as well as in connections to Sweden, to increase the transmission capacity. In certain conditions the interaction between series compensated network and wind power plants may cause unstable subsynchronous oscillations. In Finland many new wind power generation sites will be built in the vicinity of the series compensated network, thus increasing the risk of subsynchronous oscillation phenomena.

The subsynchronous oscillations can cause a disconnection of significant amount of wind power production and possibly damages in the wind turbines or series capacitors. This master's thesis investigates the amount of potentially disconnecting wind power production capacity in the Finnish transmission system due to the subsynchronous oscillation phenomena and develops methods for validating the need and functionality of the subsynchronous oscillation protections in the wind turbines.

The doubly-fed induction generator based (Type-3) wind turbines are identified to have a significant risk of causing undamped subsynchronous oscillations, while the full power converter based (Type-4) wind turbines are found to be generally immune to subsynchronous oscillation phenomena. The immunity of a single manufacturer Type-4 wind power plant model is also validated in the thesis. The maximum amount of potentially disconnecting wind power production capacity in single substation is defined using the estimated amount of production capacity from wind power plants with Type-3 wind turbines.

The conservative estimations show that the highest amount of potentially disconnecting production capacity could be in range of 340–775 MW in 2022, 520–1225 MW in 2027 and 850–2225 MW in 2030. Fortunately, the amount of disconnecting wind power is likely not as great as the conservative estimation leads to believe, for example due to the risk of undamped subsynchronous oscillation being higher when the output power of the Type-3 wind turbine is lower. Defining more precise estimations will require additional studies in the future.

The method for validating the need of subsynchronous oscillation protection in Type-4 wind turbines is developed in the thesis. The proposed method consists of three steps: 1) validation of the immunity to subsynchronous oscillations, 2) defining the worst-case scenario using parallel connected generic Type-3 wind power plant, and 3) discussions with the wind turbine manufacturer. It is proposed that if the investigated Type-4 wind turbines are not found to cause undamped subsynchronous oscillations itself and can withstand the worst-case subsynchronous oscillations caused by another nearby wind power plant, the specific subsynchronous oscillation protections should not be mandatory for the investigated wind turbine model. The method was illustrated on a single manufacturer Type-4 wind power plant model.

Validating the functionality of Type-3 wind turbine subsynchronous oscillation protection can be performed for example by first injecting subsynchronous voltage or current of certain frequency on top of the fundamental voltage or current in the wind turbine terminal, and by varying the magnitude and the frequency of the injected current or voltage. Second, the selectivity of the protection should be more thoroughly investigated using another parallel connected Type-3 wind power plant in order to validate that the wind turbines that are most significantly causing the oscillations are disconnected first in the subsynchronous oscillation event.

Keywords: Subsynchronous oscillations, SSO, Subsynchronous control interaction, SSCI, Wind related subsynchronous control interaction, W-SSCI, wind power, series compensation

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TIIVISTELMÄ

Riku Korhonen: Alisynkroninen vuorovaikutus tuulivoimaloiden ja sarjakompensoidun verkon välillä Suomessa
Diplomityö
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Sarjakompensointia on käytetty Suomessa kasvattamaan sähkön siirtokykyä pohjoisesta Suomesta eteläiseen Suomeen, sekä Ruotsin vaihtosähköyhteyksillä. Sarjakompensoidun verkon ja tuulivoimaloiden välillä on mahdollista syntyä alisynkronista vuorovaikutusta, joka voi aiheuttaa vaimentumattomia alisynkronisia värähtelyitä. Tulevaisuudessa huomattava määrä tuulivoimaa tullaan liittämään Suomessa sarjakompensoidun verkon läheisyyteen, mikä kasvattaa merkittävästi alisynkronisen vuorovaikutuksen riskiä.

Alisynkroniset värähtelyt saattavat aiheuttaa merkittävän määrän tuulivoiman irtoamista, sekä mahdollisesti myös vaurioita tuuliturbiineissa tai sarjakondensaattoreissa. Diplomityössä arvioidaan alisynkronisten värähtelyiden takia irtoavan tuulivoimatuotannon määrää Suomen kantaverkossa, sekä kehitetään menetelmiä, joilla voidaan määrittää tuuliturbiineja alisynkronisilta värähtelyltä turvaavien suojauksien tarvetta sekä odotettua toimintaa.

Kaksoissyötetyllä epätahtigeneraattorilla toimivalla tyypin 3 tuuliturbiinilla on tunnistettu olevan merkittävä riski joutua alisynkroniseen vuorovaikutukseen sarjakompensoidun verkon kanssa, johtaen tuuliturbiinin irtoamiseen verkosta. Täyden tehon taajuusmuuttajalla toimivat tyypin 4 tuuliturbiinit on todettu tavallisesti olevan immuuneja alisynkronisille vuorovaikutuksille. Yksittäisen tyypin 4 valmistajamallin immuniteetti validoitiin työssä. Alisynkronisten värähtelyiden takia tietyllä sähköasemalla mahdollisesti irtoavan tuulivoiman maksimimäärä arvioidaan asemalla olevien tyypin 3 tuulivoimaloiden tuotantokapasiteetin perusteella.

Konservatiivisten arviointien perusteella alisynkronisen vuorovaikutuksen seurauksena suurin irtoava määrä tuulivoimatuotantoa voisi olla 340–775 MW vuonna 2022, 520–1225 MW vuonna 2027 ja 850–2225 MW vuonna 2030. Toisaalta pohdintojen perusteella todennäköisesti irtoava tuulivoiman teho olisi kuitenkin todellisuudessa reilusti alle konservatiivisen arvion johtuen esimerkiksi siitä, että tyypin 3 turbiinin riski joutua vuorovaikutustilanteeseen on suurempi mitä alhaisempi turbiinin tuottama hetkellinen teho on. Jatkotutkimukset ovat tulevaisuudessa tarvittavia tarkempien arvioiden selvittämiseksi.

Tarve alisynkronisilta värähtelyiltä suojaavalle suojausfunktiolle tyypin 4 tuuliturbiineissa voidaan määrittää työssä kehitetyllä menetelmällä. Ehdotettu menetelmä koostuu kolmesta toimenpiteestä: 1) tyypin 4 laitoksen immuniteetin varmistaminen, 2) pahimman tilanteen määrittely käyttäen rinnalle kytkettyä geneeristä tyypin 3 tuulivoimalaitosta, ja 3) keskustelut tutkitun tyypin 4 tuuliturbiinin laitevalmistajan kanssa. Työssä ehdotetaan, että jos tutkittu tyypin 4 tuuliturbiini ei aiheuta alisynkronisia värähtelyitä ja kestää geneerisen tyypin-3 tuulivoimalaitoksen aiheuttaman pahimman vuorovaikutustilanteen, suojausfunktiota alisynkronisia värähtelyitä vastaan ei tarvitsisi vaatia kyseiseltä tuuliturbiinimallilta. Kehitettyä menetelmää käytettiin työssä yhden tyypin 4 valmistajamallin validointiin.

Tyypin 3 tuuliturbiinin suojauksen toimintaa voidaan validoida syöttämällä alisynkronista virtaa tai jännitettä tuuliturbiinin terminaaliin, ja tutkimalla suojan toiminta-aikaa eri syötetyn virran tai jännitteen voimakkuudella ja taajuudella. Suojan selektiivisyyttä täytyy kuitenkin tutkia tarkemmin käyttämällä vähintään toista tyypin 3 tuulipuistomallia rinnalla, ja tutkimalla toimiiko suojat oikein, kun jompikumpi laitoksista pääasiassa aiheuttaa alisynkroniset värähtelyt.

Avainsanat: Alisynkroninen värähtely, SSO, SSCI, W-SSCI, tuulivoima, sarjakompensointi

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

PREFACE

This Master of Science thesis was written in Power System Engineering unit of Fingrid Oyj. The examiner of the thesis was Professor Sami Repo from Tampere University, and advisor of the thesis was Olli-Pekka Janhunen from Fingrid Oyj. The steering group members from Fingrid Oyj were Olli-Pekka Janhunen, Liisa Haarla, Antti Harjula, Tuomas Rauhala, Antti Kuusela, Teemu Hänninen and Lasse Linnamaa.

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Riku Korhonen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

ADRC	Active disturbance rejection control
DFIG	Doubly fed induction generator
EMT	Electromagnetic transient
FACTS	Flexible ac transmission system
GCSC	Gate-Controlled series capacitor
GSC	Grid side converter
HVDC	High-voltage direct current
IGBT	Insulated gate bipolar transistor
IGE	Induction generator effect
LVRT	Low voltage ride through
MMAC	Multiple-model adaptive control
MOV	Metal oxide varistor
MPPT	Maximum power point tracking
MSC	Machine side converter
PCC	Point of common coupling
PLL	Phase-locked-loop
PMSG	Permanent magnet synchronous generators
RMS	Root mean square
RSC	Rotor side converter
SSCI	Subsynchronous control interaction
SSO	Subsynchronous oscillations
SSSC	Static synchronous series capacitor
STATCOM	Static synchronous compensator
SVC	Static var compensator
TCSC	Thyristor controlled series capacitor
TSO	Transmission system operator
VSC	Voltage source converter
W-SSCI	Wind related subsynchronous control interaction
WPP	Wind power plant

φ_{Z}	Voltage source impedance phase angle
C_{L}	Series capacitor capacitance
$COMP$ %	Compensation level (percentage) of the series compensated transmission line
C_{system}	Total capacitance of the observed system
f_0	System nominal frequency
f	Frequency of the system
f_{er}	Resonant frequency of the system
f_{r}	Frequency of the induction generator rotor
f_{s}	Frequency of the induction generator stator
I_C	RMS value of the capacitor current
k	Compensation level of the series compensated transmission line
l	Length of the series compensated transmission line
L_{L}	Series compensated transmission line inductance
L_{m}	Type-3 wind turbine magnetizing branch inductance
L_{n}	Inductance of the rest of the modelled network
L_{r}	Type-3 wind turbine rotor inductance
L_{s}	Type-3 wind turbine stator inductance
L_{source}	Voltage source inductance
L_{system}	Total inductance of the observed system

R	Resistance of the transmission lines used in the PSCAD simulations
R_{L}	Series compensated transmission line resistance
R_{n}	Resistance of the rest of the modelled network
R_{r}	Type-3 wind turbine rotor resistance
R_{s}	Type-3 wind turbine stator resistance
R_{source}	Voltage source resistance
S	Strength of the voltage source
s	Slip of the induction generator
U_{b}	Voltage source nominal voltage
U_{C}	Voltage over the series capacitor calculated by the series capacitor overload protection
X_{C}	Series capacitor reactance
X_{L}	Inductive reactance of the transmission lines used in the PSCAD simulations
X_{leakage}	Leakage reactance of the transformers used in the PSCAD simulations
Z_{GSC}	Type-3 wind turbine GSC impedance
Z_{RSC}	Type-3 wind turbine RSC impedance

1. INTRODUCTION

1.1 Background

Increasing wind power penetration is an important part of creating a clean energy system. However, modern wind power plants (WPP) that are connected to a series compensated or weak ac transmission network can reduce the damping of subsynchronous oscillations (SSO) which could lead to disconnection of large amounts of wind power production or possibly damages in the wind turbines and transmission equipment [1].

Subsynchronous oscillation is a result of adverse interaction between two or more power system components, such as wind turbine and series capacitor. It is a condition where the components are exchanging energy at one or more frequencies below the system nominal frequency [2]. Doubly fed induction generator (DFIG) wind turbines (Type-3) could have a high negative damping in subsynchronous frequencies due to inherent characteristics of the induction generator, and due to the characteristics of the partial scale converter [3]. If the WPP provides negative damping on the network resonant frequency, which is formed by the series connection of system inductances and series capacitance, undamped or sustained subsynchronous oscillation can appear. The full converter (Type-4) wind turbines can have negative damping in subsynchronous frequencies when connected to a weak network [4], and potentially when connected to a series compensated network [5].

In the Finnish transmission system, series compensation has been used at main power transfer routes between northern and southern Finland, as well as in connections to Sweden, to increase the transmission capacity [6]. Series compensation has a significant impact on transmission capacity, and at present it is estimated to more than double the transmission capacity from northern Finland to southern Finland, compared with the capacity without the compensation. In a near future many new wind power generation sites will be built in the vicinity of the series compensated network, thus increasing the relevance of the subsynchronous oscillation phenomena. According to recent generic subsynchronous oscillation risk assessments made by Fingrid, the Finnish transmission system operator (TSO), there is a rather significant subsynchronous oscillation related risks between WPPs and series capacitors, and thus further investigations are required. [7]

The first specific study requirements for converter-connected power plants in vicinity of Fingrid’s series compensated network was released in early 2021 [8].

1.2 Motivation and objectives

The risk of undamped and high amplitude subsynchronous oscillation, especially considering Type-3 WPPs, is greater when the WPP is connected in the vicinity of a series compensated network. In the near future, wind power production near the series compensated network of Finland is greatly increasing. As the subsynchronous oscillation phenomena can cause large-scale disconnections of wind power production and damages in the wind turbines or the series capacitors, the investigations regarding the amount of wind power production disconnection and the subsynchronous oscillation damping and protection abilities of the WPPs are required. The objective of this master’s thesis can be divided into following two parts.

The first part investigates the maximum amount of potentially disconnecting wind power production capacity due to the subsynchronous oscillation phenomena, which may create a system level risk if the amount is high. In this part, an estimate for maximum amount of wind power production capacity that could be potentially disconnected in different future scenarios of the Finnish transmission system due to the subsynchronous oscillation phenomena between WPPs and series compensated network is established.

In the second part, methods are developed to define the need and functionalities of different wind turbines’ subsynchronous oscillation protections. At present, the functionality of the protections is not precisely defined in the requirements, and thus the implementation of these protections could differ greatly. Also, in some cases there might be no need for the specific subsynchronous oscillation protections in the wind turbine if the risk of subsynchronous oscillation for the wind turbine is considered low enough. Therefore, methods are needed in order to validate the actual need of specific subsynchronous oscillation protections in the wind turbines, and in order to better validate the desired protection functionalities.

The research questions are the following:

1. What is the greatest amount of potentially disconnecting wind power production capacity due to the undamped subsynchronous oscillation phenomena in the different future scenarios of the Finnish series compensated transmission network, and what are the critical locations?
2. How the need and the functionality of the subsynchronous oscillation protections could be validated for different wind turbines?

1.3 Structure

Chapter 2 presents a literature review of the subsynchronous oscillation phenomena related to Type-3 and Type-4 wind turbines connected to a series compensated network. The chapter also includes the main factors affecting the risk undamped subsynchronous oscillation in both wind turbine types, as well as the cause of possible damages in series capacitors and wind turbines are discussed. In Chapter 3, the subsynchronous oscillation studying methods and tools as well as methods for mitigating the subsynchronous oscillations are presented, along with findings from real-world subsynchronous oscillation events involving WPPs and series capacitors. Chapter 4 will present the different future scenarios of the Finnish transmission system, considering the amounts of wind power production capacity connected to different investigated substations. Chapter 5 will present the simulation and research methods used in the thesis to answer the research questions. Results of the simulations are presented in Chapter 6 and the results as well as the suggested future research subjects will be discussed in Chapter 7. Chapter 8 includes the conclusion of the thesis.

2. SUBSYNCHRONOUS OSCILLATION PHENOMENA

In Chapter 2, the main objective is to provide the basic idea of subsynchronous oscillation phenomena between the Type-3 and Type-4 WPPs and a series compensated network. Section 2.1 presents the essential definitions and terms. Sections 2.2 and 2.3 discuss the general configurations and the subsynchronous oscillation phenomena regarding Type-3 and Type-4 WPPs, respectively. In Section 2.4 the main factors that affect the damping and frequency of the subsynchronous oscillation will be discussed. Finally, the damages in series capacitors and wind turbines in case of high amplitude subsynchronous oscillation will be reviewed in Section 2.5.

2.1 Definitions and terms

Subsynchronous oscillation is a basic term and can be defined as oscillation between two or more power system elements, where the elements are exchanging significant energy at one or more frequencies below the system nominal frequency. These elements can be for example turbine-generators, series capacitors or power electronics. [2, p. 1012]

Oscillations in subsynchronous frequencies occur frequently in series compensated power systems for example due to faults and switching events. These oscillations are usually well damped due to the positive damping provided by the passive grid components. However, a WPP could have negative damping at certain frequencies, which could lead to undamped subsynchronous oscillation if the negative damping exceeds or is equal to the positive damping provided by the passive grid components in the resonant frequency. In other words, if the resonant frequency of the system changes, for example due to a nearby transmission line outage, to a range where the WPP provides negative damping, there is a risk of undamped subsynchronous oscillation. The resonant frequency and corresponding damping of the frequency are also sometimes referred to collectively as the oscillation mode. These oscillations can be harmful, because when undamped they cause high amplitude currents and voltages that can lead to the disconnection of generation units, which in the worst case could lead to wide-spread outage. The oscillations could also cause damages in the power system equipment or in generation units if they are not properly protected against the subsynchronous oscillation phenomena.

The subsynchronous oscillation phenomena in Type-3 and Type-4 WPPs connected to a series compensated network can be divided into two categories. Generally, interactions between power electronics devices or control systems and series capacitors are called subsynchronous control interactions (SSCI) [2, p. 1013] [9, p. 2]. Regarding the Type-4 WPPs connected to a series compensated network, the subsynchronous oscillation is a result of the interaction between the full-scale power electronics controllers of the wind turbines and series capacitors, thus it is referred to as SSCI. However, in Type-3 WPPs connected to a series compensated network, the subsynchronous oscillation is a result of both induction generator effect (IGE) explained in Section 2.2.2, and interaction between power electronics converters of the wind turbines and series capacitors, and it is referred to as wind related subsynchronous control interaction (W-SSCI) in this thesis. The subject of mechanical parts of the wind turbines, for example the turbine drive-train or the blades of the turbine, being part of the interactions is also touched upon and will be referred to as torsional interaction.

It should be noted that Type-3 and Type-4 WPPs could also interact with networks without series compensation [10, p. 1] [4, p. 4708]. Regarding Type-3 WPPs this has been quite rare since it seems that only one such event has been observed [10, p. 2]. Regarding Type-4 WPPs however, interactions with an uncompensated network seem to have been historically more common, but there have not yet been reported events where Type-4 WPP had interacted with a series compensated network [11, p. 2]. However, in this thesis only the subsynchronous oscillation phenomena regarding the Type-3 and Type-4 WPPs and a series compensated network will be discussed.

2.2 Type-3 wind power plants in series compensated network

2.2.1 Type-3 wind turbine configuration

Type-3 wind turbines consist of DFIGs, which are connected to the network both directly and through a power electronics converter, as presented in Figure 1. The stator of the generator is directly connected to the grid and the rotor is connected to the grid through a partial scale power converter. The power converter consists of two voltage source converters (VSC), namely rotor side converter (RSC) and grid side converter (GSC) which are connected with a dc link, containing a dc capacitor. [12, pp. 37,38].

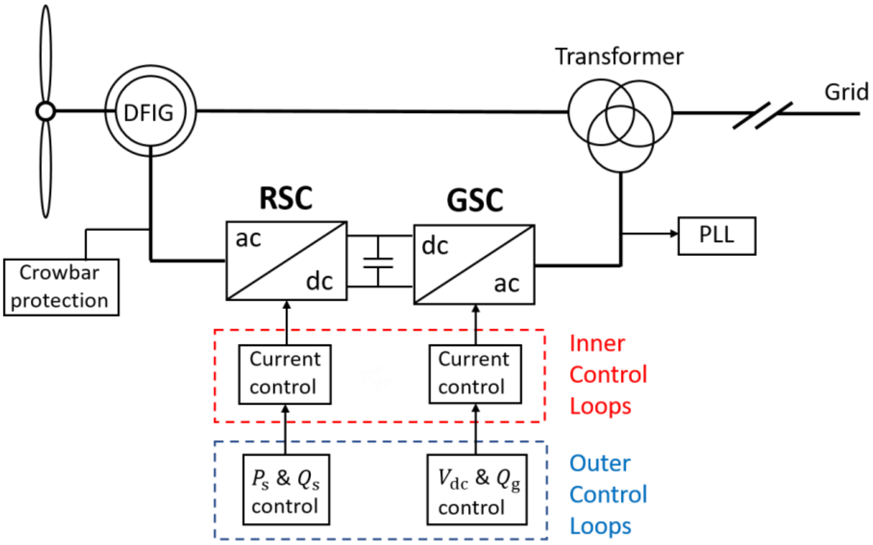

Figure 1: Schematic diagram of Type-3 wind turbine and converter control loops

Regarding the subsynchronous oscillation phenomena, the most important wind turbine controls are the controls of the RSC and the GSC. The RSC and the GSC are both controlled with two-level control loops that work independently as presented in Figure 1. In the RSC, the outer control loop can control the stator active and reactive power. In the GSC, the outer control loop can control the dc-link voltage and GSC grid side reactive power output. [12, pp. 37, 38] The inner control loops are significantly faster compared with outer control loops, and they make sure that the currents flowing through the RSC and the GSC stay at the reference value determined by the outer loops. The phase-locked-loop (PLL) is used to convert the three-phase ac measurements to the rotating reference frame (dq frame) dc signals, that are used by the converter control loops. The crowbar circuit protects the RSC and the dc-link from overcurrent and overvoltage.

The control strategy for the RSC outer loop is to regulate the active and reactive power outputs of the stator, according to maximum power point tracking (MPPT) algorithm and reference value provided by the WPP voltage control, respectively [11, p. 52] [12, pp. 37,38]. The control strategy for the GSC outer loop is to keep the dc-link voltage constant and assists in grid side voltage control when additional reactive power is required [12, p. 37].

2.2.2 Induction generator effect

Generally, subsynchronous oscillation phenomena regarding Type-3 wind turbines appear when the WPP has a radial or close to a radial connection with series compensated line. The equivalent impedance model of the purely radial connection is shown in Figure 2. The magnetizing branch inductance L_{m} and the GSC impedance Z_{GSC} are assumed to have high impedance, and thus are ignored [11, p. 5]. The effect of RSC impedance

Z_{RSC} will be discussed later in Sections 2.2.3 and 2.4.5 and can be ignored for now to simplify the arrangement. The connecting transformer and the connection line of the WPP would only provide relatively small amount of resistance and inductance to the series connection, and thus it is also can be ignored here for simplification. The resistances of the Type-3 wind turbine rotor circuit and stator, series compensated transmission line and the rest of the network are represented by R_{r}/s, R_{s}, R_{L} and R_{n}, respectively.

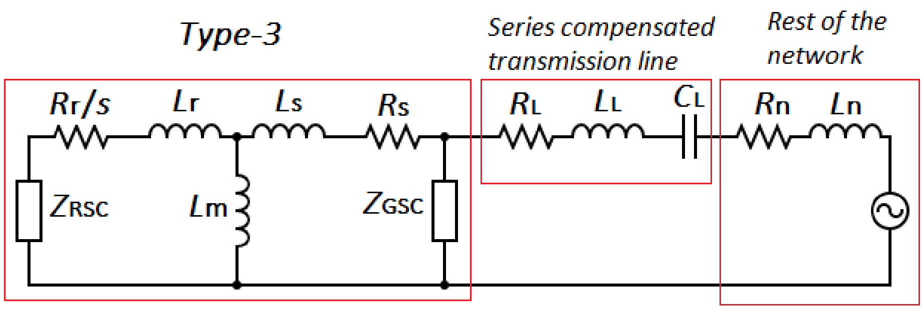

Figure 2: Equivalent circuit of a Type-3 wind turbine connected to series compensated network

Capacitance of the series capacitor (C_{L}), and the inductances of the series compensated transmission line (L_{L}), wind turbine rotor and stator (L_{r} and L_{s}) and the rest of the network (L_{n}) can form the electrical series resonance circuit. Thus, when the series resonance circuit total capacitive reactance is equal to total inductive reactance, the WPP can resonate with the series compensated network resulting in subsynchronous oscillation. Frequency at which this series resonance occurs is generally called natural frequency or the resonant frequency of the system. This frequency can be defined by:

$$f_{\mathrm{er}} = \frac{1}{2\pi}\sqrt{\frac{1}{L_{\mathrm{system}} C_{\mathrm{system}}}} \tag{1}$$

where the f_{er} is the resonant frequency of the system, and the L_{system} and C_{system} are the total inductance and capacitance of the observed system, respectively.

The damping of subsynchronous oscillation in traditional synchronous turbine-generators consists of mechanical and electrical damping. However, the mechanical damping is usually ignored due to its low contribution to total damping. Thus, only the electrical components are considered and the damping of the generator is mainly determined by the resistances of the generator. [13, p. 1329] [14, p. 55] Similar approach can be used to gain conservative results when investigating the damping of the Type-3 wind turbine.

The resistance of the Type-3 wind turbine rotor circuit can be represented as:

$$\frac{R_\mathrm{r}}{s} \tag{2}$$

where R_r is the resistance of the rotor and s is the slip of the generator [15, p. 289] which is defined as:

$$s = \frac{f_\mathrm{s} - f_\mathrm{r}}{f_\mathrm{s}} \tag{3}$$

where f_s and f_r are the frequencies of the stator and rotor, respectively.

In normal operation, the induction generator needs a negative slip to be able to produce active power. The more power an induction generator produces, the higher rotor frequency and thus higher negative slip. However, a stator subsynchronous frequency, which is coming from the network and is lower than the rotor frequency, will also create negative slip according to Equation (3) that will lead to negative rotor circuit resistance at that frequency according to Equation (2). Therefore, if the absolute value of the negative resistance of the rotor at the resonant frequency is greater than or equal to the sum of stator and network resistances, the oscillations at that subsynchronous frequency will be undamped or sustained. This is called the induction generator effect.

2.2.3 Torsional interactions

Since part of the Type-3 wind turbine is directly connected to the grid, oscillations involving the mechanical parts of the turbine are also possible, at least in theory. This interaction between the electrical and mechanical system is termed torsional interaction. The torsional mode frequencies, corresponding to mechanical oscillation modes of the turbine drive-train, are normally in range of 1–5 Hz in Type-3 wind turbines due to low shaft stiffness coefficients [16, p. 817]. The torsional mode frequencies in range of 1–5 Hz correspond to the complementary network frequencies of 45–49 Hz for 50 Hz systems. In other words, subsynchronous oscillations in frequency of 45–49 Hz are required for torsional interaction to possibly occur in Type-3 wind turbines.

The series compensation level ($COMP$ %) of the transmission line is defined as:

$$COMP\ \% = \frac{1}{(2\pi f_0)^2 L_\mathrm{L} C_L} 100\ \% \tag{4}$$

where f_0 is the system nominal frequency, L_L is the inductance of the transmission line and C_L is the capacitance of the series capacitor [14, p. 16]. The maximum series compensation level used in the Finnish transmission network is 85 % [17]. If only the series compensated transmission line is considered, according to Equations (1) and (4) using maximum series compensation level of 85 % the maximum resonant frequency will be

46,1 Hz. Taking the generally inductive Type-3 WPPs and the rest of the network inductances into account, the maximum frequency will be always less than this. With lower compensation levels the maximum resonant frequency will also be lower. Therefore, it can be concluded that the torsional interaction is not prominent phenomenon considering practical Type-3 wind turbines.

2.2.4 Converter controller interactions

The control parameters of the Type-3 WPP converters have a significant impact on the subsynchronous oscillation damping ability. Both GSC and RSC controls have influence, however the impact of RSC is found to be much stronger compared with GSC. This is logical since the RSC controls the induction generator, which can provide negative damping due to the induction generator effect, and the GSC only controls the dc link voltage and converter output. Also, while the RSC outer control loop can have effect, the effect of the converters on the damping of the subsynchronous oscillations is mainly caused due to the fast inner control loop of the RSC. [18, pp. 2777,2779] [9, pp. 3,4]. The PLL can have effect on the impedance characteristic of Type-3 WPP, however the effect of PLL is not as great as the outer loop controls according to [19, p. 158387], which as mentioned before do not have as great impact on subsynchronous oscillation damping as the inner loop controls. Therefore, in case of Type-3 WPPs the PLL parameters can be considered to have a relatively small contribution to the damping of subsynchronous oscillations, compared with the parameters of RSC controls. The effect of different parameters of the converter controls on the damping, as well as other participating factors, are discussed more in Section 2.4.

All in all, regarding Type-3 WPPs, the subsynchronous oscillation is generally a result of both induction generator effect and converter controller interactions [3, p. 1125], and it is here referred to as W-SSCI. The risk of W-SSCI is considerable especially in cases where the Type-3 WPP has a radial or close to a radial connection with series capacitor. Since W-SSCI is purely electrical phenomenon, the undamped oscillations can also grow to dangerous levels quickly.

2.3 Type-4 wind power plants in a series compensated network

2.3.1 Type-4 wind turbine configuration

Type-4 wind turbines generally consist of permanent magnet synchronous generators (PMSG) and use full-scale power converter to connect to the grid, as presented in Figure

3. The power converter consists of two VSCs, the machine side converter (MSC) and GSC. [12, pp. 85,86]

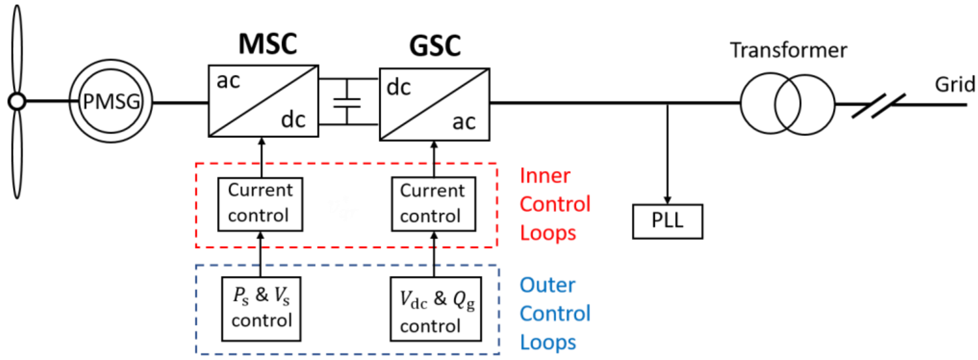

Figure 3: Schematic diagram of Type-4 wind turbine and converter control loops

Regarding the subsynchronous oscillation phenomena, the most important wind turbine controls are the controls of MSC and GSC, as well as the PLL. The MSC and GSC of the Type-4 wind turbines are also controlled with two-level control loops as represented in Figure 3. The inner control loops make sure that the controlled converter current stays at the value determined by the outer loops. In the MSC, the outer control loop can control the PMSG active power output and the stator voltage, and in the GSC the outer control loop can control the dc link voltage and the ac side reactive power output. [12, pp. 98-107] Thus, the converter controls of the Type-4 wind turbines are similar to the Type-3 wind turbine converter controls, however the differences are in the control strategies. The controls also include a PLL, which parameters have significant effect on the damping of subsynchronous oscillation in the Type-4 wind turbine.

The control strategy of the MSC is generally to regulate the active power output of the PMSG according to the maximum power point tracking algorithm, and to keep the stator voltage constant in its rated value when using the constant stator voltage control mode. There are also other control modes for the MSC, for example the unit power factor control mode where the PMSG reactive power output is kept at zero. The control strategy of the GSC is generally to keep the dc voltage constant and provide grid side reactive power support when required. [12, pp. 99-101, 105]

Since the mechanical side of the turbine is isolated from the grid by this full-scale power converter, the torsional interactions are not possible [1, p. 164] and neither is the induction generator effect, and the only element contributing to the potential subsynchronous oscillation phenomena is the full-scale power converter.

2.3.2 Subsynchronous control interaction

The subsynchronous oscillation phenomena observed in real-life Type-4 WPPs have been a result of interactions between Type-4 WPPs and networks with large reactance and no series compensation, or in other words weak networks, which lead to undamped subsynchronous oscillation. This has been termed as weak grid subsynchronous oscillation. [11, pp. 2,3]

According to certain theoretical and practical observations, the Type-4 WPPs in a series compensated networks are immune to the SSCI phenomenon and behave passively when exposed to undamped subsynchronous current and voltage oscillations caused for example by the nearby Type-3 WPPs although it is noted that such results should not be generalized lightly, due to the numerous possibilities regarding the control parameters [3, p. 1125] [20, p. 5]. Therefore, the possibility of the Type-4 WPP to cause undamped SSCI by itself in the Finnish series compensated network could be considered low.

However, according to recent studies [5] [21] [22], there is a possibility of undamped SSCI in Type-4 WPPs connected to a series compensated network. In these recent studies, the GSC is found to have a major role in the interaction between Type-4 WPPs and series capacitors, thus this phenomenon could be defined as SSCI. The oscillations are possible if the GSC provides negative damping on frequency close or the same as the system resonant frequency.

According to a recent study [22], an undamped SSCI mode between Type-4 WPP and a series compensated network is possible in certain conditions and the interaction is primarily caused by the GSC. It is also found that the oscillation frequency is strongly related to the electrical resonant frequency of the system, similar to the Type-3 WPPs. [22, p. 616]

In another recent study [5], the effect of the network strength as well as the GSC on system stability regarding Type-4 WPPs is also highlighted. Normally, increasing the network strength without series compensation makes the system more stable. However, when the series compensation is used in an otherwise weak network, the system can actually become more unstable, depending on the parameters of GSC and PLL. [5, p. 529] Specifically, the parameters of the PLL can determine whether the increase of series compensation level improves the stability or makes it worse. [5, pp. 533, 535] In [23] the PLL and the outer loop controls are identified as the main reasons for the subsynchronous oscillation in grid connected voltage source converters.

All in all, the subsynchronous oscillation phenomenon SSCI in Type-4 wind turbines connected to series compensated network is caused by the full-scale power converter controls and thus it is here referred to as SSCI. The risk of Type-4 WPPs being the major reason for undamped SSCI can be considered fairly low, due to the immunity and passivity observed in some studies, and absence of real-life events. However, according to the recent literature there could be a possibility for interactions, thus the SSCI immunity of the Type-4 WPPs should not be assumed.

2.4 Participating factors

There are numerous factors impacting frequency and damping of the W-SSCI and SSCI, and some of the most significant ones are presented next.

2.4.1 Network topology and strength

The Radial or close radial connections of the Type-3 WPP with series capacitors usually enables the electrical series resonance, thus creating possibility for W-SSCI. In all real-world W-SSCI events, the undamped oscillations have appeared only when the WPPs were radially connected to the series capacitor, or when all the significant parallel connection were series compensated, as it is discussed in Section 3.3. Therefore, according to the real-life cases, contingencies where the Type-3 WPP is left connected to the rest of the network only through series compensated lines could be considered as the most dangerous conditions regarding the W-SSCI phenomenon.

However, according to results from a subsynchronous oscillation study (an internal report commissioned by Fingrid [24]), the damping of the Finnish transmission network observed from a certain point can reach low values in certain contingencies, without pure radial connection with a series capacitor or even though all the significant connections are not series compensated. Thus, according to the study, the W-SSCI risk could be considerable also in cases where the Type-3 WPP has significant uncompensated connections with the rest of the network, if the damping of the network is sufficiently low.

From the results of study [24] it can be concluded that the risk of W-SSCI at least in the Finnish highly meshed series compensated transmission system is not easily deducible only by looking at the topology of the network at the WPP connection point. Instead, the risk should be investigated by calculating the damping of the network side in numerous different contingencies, as was done in the aforementioned study. The effective resistance or the damping factor in a network resonant frequency could be used to depict the damping of the network at certain location. However, more studies are required in order to estimate the level of damping that could be considered as a risk for W-SSCI. The 400 kV highly meshed series compensated part of the Finnish transmission system in three different future scenarios is presented in Appendix C.

In the study presented at [21], the risk of SSCI was not found with Type-4 WPPs when an uncompensated line was connected parallel with a series compensated line that was connecting the Type-4 WPP to the rest of the network [21, p. 1417].

2.4.2 Series compensation level

The effects of series compensation level on W-SSCI frequency and damping in Type-3 WPPs can be partly deduced from the Equations (1)–(3) in Section 2.2.1. Increasing the series compensation level means increasing the series capacitive reactance of the system, or in other words decreasing the capacitance of the series resonance circuit. Thus, according to Equation (1) it will also increase the resonant frequency. As the resonant frequency seen in the stator of the Type-3 wind turbine increases, according to Equation (3) the absolute value of the negative slip will decrease, which according to Equation (2) will make the equivalent rotor resistance appear more negative, thus decreasing the damping of the W-SSCI.

In other words, on higher compensation levels the frequency of the oscillation is generally higher, and the damping of the Type-3 wind turbines induction generator is lower. Damping provided by the converter is not as easily deduced, as it could be better or worse depending on the numerous parameters and control schemes of the converter. Undamped W-SSCI can appear even on low compensation levels. For example, W-SSCI event happened in wind power system in northern China where the compensation level of the whole system seen by the Type-3 WPP was only 6.67 %, and thus low resonant frequencies of 6~8 Hz were observed [18, p. 2772]. At oscillation frequencies this low, the induction generator effect is not as strong as the negative resistance of the rotor is smaller according to Equations (1) and (2). This means that the negative resistance must have been caused more by the converter controller interaction in the Type-3 wind turbines.

In Type-4 wind turbines the effect of series compensation can depend on how the PLL is implemented, as mentioned in Section 2.3.1. According to a study [5], in weak networks if the bandwidth (speed) of the PLL is lower (13 Hz in the study), the increase of series compensation level leads to better damping. However, if the PLL bandwidth is higher (32 Hz in the study), the increase of series compensation level will decrease the system stability. [5, pp. 533, 535]

2.4.3 Number of online wind turbines

Wind turbines are usually connected in parallel in the WPP. Increasing the number of parallel connected Type-3 wind turbines, which are typically inductive in the subsynchronous frequency range, decreases the total inductive reactance, or in other words decreases the total inductance, seen from the network. Therefore, the total system inductance decreases, which according to Equation (1) will increase the system resonant frequency. Similarly, decreasing the number of parallel connected Type-3 wind turbines will decrease the system resonant frequency. However, the number of online Type-3 wind turbines can have a nonlinear relationship with the system damping, depending on the parameters of the series compensated line [25, p. 8] and wind speed [18, p. 2776].

The Type-4 WPP equivalent impedance can be either inductive or capacitive in the subsynchronous range depending on the frequency [26, pp. 2,3]. Thus, the effect of increasing or decreasing the number of Type-4 wind turbines depends on the resonant frequency in the WPP connection point. If the resonant frequency is in range where the Type-4 WPP appears inductive, the effect is similar as in Type-3 wind turbines and the increase of parallel Type-4 wind turbines increases the resonant frequency. However, if the resonant frequency is in range where the Type-4 WPP equivalent impedance appears capacitive, the effect is opposite and increasing the number of wind turbines will lower the resonant frequency.

2.4.4 Wind speed

The maximum power point tracking of the Type-3 wind turbine looks up the optimal rotor speed according to the wind speed. The wind speed is proportional to rotor speed, excluding when it is above the rated wind speed or below the cut-in wind speed [12, pp. 133,134]. Thus, higher wind speed generally results in faster rotor rotation speed, which results in higher output power and rotor frequency. When the rotor frequency is higher than the stator frequency (network frequency), the negative slip is achieved according to Equation (3). In induction generators, the slip is always negative as the rotor frequency must be greater than stator frequency for the generator to produce power to the grid. At higher wind speeds the rotor frequency further increases compared with stator frequency, which increases the absolute value of the negative slip. According to Equation (2) this results in smaller absolute negative resistance in the Type-3 wind turbines induction generator. Thus, higher wind speed generally results in the improved damping of the system, regarding Type-3 WPPs. In other words, the damping of subsynchronous oscillation is worse on lower output power levels.

The effect of wind speed on Type-4 WPPs connected to a series compensated network has not been mentioned in the literature although it is noted that higher active power output affects the system damping negatively [21, p. 1415].

Wind speed can also affect the number of wind turbines connected to the system, which are disconnected if the wind speed is below the cut-in speed or above the cut-out speed. Changing wind speed can thus change the number of connected wind turbines and therefore, as mentioned in Section 2.4.3, also change the resonant frequency.

2.4.5 Wind turbine converter controller parameters

As mentioned in Section 2.2.4, the RSC of the Type-3 wind turbine has stronger impact on W-SSCI compared with GSC. More specifically, the proportional gain of the RSC inner control loop, has the greatest impact. It can change the equivalent impedance of the whole Type-3 wind turbine seen from the network side, thus affecting both the system damping and resonant frequency. Increasing the proportional gain leads to more negative damping and lower resonant frequency. Other impactful parameters are the proportional gains of the stator reactive power control and the dc voltage control, which both affect damping and resonant frequency in Type-3 wind turbines. [18, pp. 2777, 2779] As discussed in Section 2.2.4 the PLL parameters can be considered to have relatively small contribution to the damping of subsynchronous oscillations in the Type-3 wind turbines.

On the contrary, in Type-4 wind turbines, the strongest impact is created by the GSC, and by the PLL parameters. As mentioned in Section 2.4.2, if the PLL bandwidth is higher, the increase of series compensation level will decrease the system stability. In the study [21] it is also found that a faster PLL will increase the risk of SSCI, however tuning the PLL too slow will create difficulties in low voltage ride through (LVRT) operations. In addition, according to the study [21] the speed of the GSC reactive power control loop also has major impact on the damping of the SSCI, and faster reactive power control loop can increase the frequency range where the oscillations are undamped in the Type-4 wind turbine, thus increasing the risk of oscillations.

2.4.6 Wind power plant interaction

There can be multiple WPPs connected to the same connection point, which means there can also be both Type-3 and Type-4 WPPs at the same connection point or at close vicinity of each other. This means that even though the Type-4 wind turbines most likely do not cause undamped SSCI by themselves, they can still be exposed to undamped or sustained high amplitude subsynchronous voltages caused by the close Type-3 wind turbines. Due to the inherent characteristics of the converters, in case of subsynchronous voltages at the connection point the Type-4 wind turbine will also start to inject subsynchronous currents [7, p. 4] although the amplitude of these currents is generally significantly lower in comparison with those injected by the Type-3 wind turbine [3, p. 1121]. However, whether the existence of Type-4 WPP at the connection point actually improves or deteriorates the damping of SSCI is still dependent on the impedance characteristics of the Type-4 wind turbine, which depends heavily on the frequency as well as on the control parameters of the converters. The response of a certain manufacturer Type-4 WPP model to undamped W-SSCI caused by a nearby Type-3 WPP is investigated in the simulations presented in Section 5.2.2, and the results of the investigation are presented in Section 6.2.

2.5 Damages in series capacitors and wind turbines

Subsynchronous currents and voltages are capable of causing damages in the series capacitors and wind turbines. How the damages can occur and the components vulnerable to damages are briefly presented next. Understanding the physical phenomena that can lead to asset failures is important when validating the protections of the equipment.

2.5.1 Series capacitor

Series compensation in the Finnish transmission network is performed with fixed series capacitors. According to present understanding, the vulnerable component in the fixed series capacitors in the presence of high amplitude subsynchronous oscillation is the capacitor itself.

The overload protection of the series capacitor calculates the voltage over the capacitor (U_C) from:

$$U_\mathrm{C} = X_\mathrm{C} I_\mathrm{C} \tag{5}$$

where I_C is the root mean square (RMS) value of the capacitor current, and X_C is the reactance of the capacitor which is calculated from:

$$X_\mathrm{C} = \frac{1}{2\pi f C} \tag{6}$$

where f is the system frequency and C is the capacitance of the capacitor.

Capacitor overload protection calculates the reactance and RMS current with nominal frequency [27]. In case of high amplitude subsynchronous currents, the capacitor reactance is greater than what is calculated by the overload protection, according to Equation (6). Also, the capacitor current is greater in reality compared with RMS value calculated. Thus, in case of high amplitude subsynchronous currents the voltage over the series capacitor is greater in reality than what is calculated by the overload protection, according to Equation (5).

The fixed series capacitor has overvoltage protection performed for example by parallel connected metal oxide varistor (MOV) that limits the voltage. During undamped subsynchronous oscillations when the voltage oscillations across the capacitor reach a certain level, the MOV will start to conduct and the voltage oscillation will be restricted to the series capacitor protective level voltage, which is the rated voltage of the MOV. In other words, the MOV limits the oscillations to the series capacitor protective voltage level. [28, p. 38] If the oscillations persist, bypassing the series capacitor might be required. However, since the voltage calculated by the capacitor overload protection is much lower than in reality, the capacitor is not bypassed quickly enough and it may be damaged.

Damages in the series capacitors were observed in a real life subsynchronous oscillation event that occurred in a Type-3 WPPs in Texas, 2009 [9, p. 2], but there seems to be no publications on events with damages in series capacitors since.

Thus, it can be concluded that in order to properly operate the system, the series capacitor overload protections should be able to take the frequency dependency of the capacitor reactance and instantaneous current values into consideration. Alternatively, a wideband band-pass filter for example could be used to detect the subsynchronous oscillations from the current or voltage measurements, and the protection could trip if the magnitude of this filtered current or voltage increases too high.

2.5.2 Wind turbine

A published subsynchronous oscillation event that resulted in damages in the Type-3 wind turbines happened in Texas, 2009, where the wind turbine crowbar circuits were damaged due to the W-SSCI. The crowbar circuit, shown in Figure 1, is used in the Type-3 wind turbines to protect the RSC and dc link capacitor against overcurrent and overvoltage, respectively. [11, pp. 16,52] During undamped W-SSCI the high amplitude subsynchronous current component is more prominent compared with the voltage component, as will be discussed in Section 3.3, which is why having a reliable current protection against subsynchronous currents in is essential to avoid asset failures at Type-3 wind turbines. Fortunately, after the aforementioned event there have not been damages in the Type-3 wind turbine considering published W-SSCI related events. Also, the protections against the W-SSCI seem to have been significantly improved, and the risk of equipment damage should be smaller than before [27]. There seems to be no other reported events describing damages in the Type-3 wind turbines considering subsynchronous oscillation phenomena. Also, there seem to be no reported events where damages in the Type-4 wind turbines are reported.

Similarly, to the series capacitors, the overcurrent and overvoltage protections of the wind turbines should be based on instantaneous current and voltage values in order to detect the subsynchronous currents and voltages, that can increase rapidly in case of undamped subsynchronous oscillation phenomena. Alternatively, a subsynchronous oscillation specific protection relay could be implemented. Regarding Type-4 wind turbines, the protections should still be included even if the wind turbine by itself is found not to cause undamped subsynchronous oscillation, since it still may be exposed to high amplitude oscillations created by any close by Type-3 WPPs, as explained in Section 2.4.6.

3. STUDYING AND MITIGATION METHODS AND REAL-WORLD EVENTS

3.1 Studying methods and tools

There is no single method that would provide comprehensive knowledge of subsynchronous oscillations, especially when considering modern WPPs with complex power converters that a have major role in the phenomena. The most commonly used methods for analysing subsynchronous oscillations in WPPs connected to a series compensated networks are frequency scanning methods, eigenvalue analysis and electromagnetic transient (EMT) analysis.

3.1.1 Frequency scanning method

In the frequency scanning method, the equivalent resistance and reactance seen from a certain point in the system is presented for all frequencies of interest [29, p. 11]. For example, this can be done by looking at the network from the connection point of the investigated WPP. The result is thus the equivalent resistance and reactance of the network side as a function of frequency, seen by the WPP. Alternatively, the result can be the impedance magnitude and angle. The calculations can be done using series and parallel connected passive network elements. The frequency scan based on the passive grid component parameters (*R*, *L* and *C*) does not consider any dynamic components in the system, such as WPPs or HVDC systems. [23, p. 18]

Similarly, the frequency scanning can be done on the WPP, by looking towards the WPP from the connection point. However, scanning the impedance of the non-linear WPP requires a dynamic scan which can be done with a more advanced current or voltage injection method [30, pp. 2, 3]. These methods are termed in this thesis as dynamic impedance scanning methods. The network side frequency scan changes with the network topology and operation conditions, and the WPP side frequency scan changes with different operation conditions and with possible adaptive controls. The adaptive controls refer to the ability of the converter to change its parameters according to the changes in the network. Especially if the converters use adaptive controls, the WPP dynamic impedance scans should be performed with many different network configurations.

The potential conditions where the undamped subsynchronous oscillation could happen can be observed by comparing the network and WPP frequency scans. As explained in Section 2.2.2, the resonant frequency and damping depend on system reactances and resistances. In [30] it is presented that identifying the potential scenarios with higher risk for the undamped subsynchronous oscillation can be done using the following criteria:

- “Any resonant condition on the system side if the turbine resistance at that SS (subsynchronous) frequency is negative. Even though the turbine reactance cross-over does not match the system resonant frequency the turbine resistance is negative at the sub-synchronous frequency at which system shows resonant conditions”
- “Any reactance crossovers on the turbine side that coincides with resonant conditions on the system side even if the resistance at the sub-synchronous frequency is positive”

In [30] these criteria are said to consider the active controls of the wind turbines, however these criteria were not validated very thoroughly. Therefore, a risk of undamped subsynchronous oscillations could be present in scenarios that do not fit the criteria presented. The first criterion is easy to understand. The negative resistance of the WPP means that the WPP will amplify oscillations, and if this matches the series resonance point (zero reactance) the risk for undamped oscillations is considerable.

The second criterion is not as easily inferential since the WPP can, according to the criterion, cause undamped oscillations even though the resistance (damping) of the WPP is positive. This is explained to be possible due to the active controls of the wind turbines, however it is not explained very thoroughly how the second criterion can identify these conditions where the active controls cause undamped oscillations regardless of the effective resistance of the WPP [30].

There is also a possibility for controller interactions in network resonance frequency that is not seen as a series resonance point from the location considered. These resonance frequencies are termed as distant resonances and they can be detected as reactance or impedance magnitude dips in the frequency scanning results. [24] In other words, these distant resonances are not series resonance points as the reactance does not cross over zero. However, the effect of the WPPs (that are not considered in the passive network side frequency scans) can change the total system impedance such that the reactance becomes zero at certain frequency, effectively creating the series resonance point.

The frequency scanning methods are useful for screening large numbers of study scenarios for the potential risk conditions. This means significant time savings when investigating larger systems. However, due to the approximations even in the most advanced frequency scanning methods, the results are not perfectly reliable and additional investigation is required on the risk conditions. Thus, these conditions should always be further investigated with more precise EMT analysis. [30, p. 3] Also, this method only investigates the small signal stability, and does not consider the WPP behaviour for example during faults.

3.1.2 Eigenvalue analysis

The eigenvalue analysis of the system offers both frequency and damping of all oscillation modes in a single calculation. The complex eigenvalues are calculated from the linear system equations, or in other words from a system state matrix. The real part of the eigenvalue represents the damping of the oscillation mode in question and the imaginary part represents the frequency of the mode. If the eigenvalue has a positive real part, the damping of the mode is negative and the system is unstable. This analysis method can also include the calculation of eigenvectors, which can be used to represent the relative effect of each variable on each oscillation mode. [29, pp. 12,13,16] Simply put, the factors that participate the most or make no contribution to the subsynchronous oscillation can be investigated. This investigation is also referred to as participation factor analysis.

The eigenvalue analysis has been particularly useful when using the participation factor analysis, which identifies the most important factors contributing to the subsynchronous oscillation phenomena in Type-3 and Type-4 WPPs. Also, the movement of the eigenvalues, which refer to changes in the frequency and damping of the oscillation modes due to different changes in the system, are easy to plot and represent. [29, p. 16] The eigenvalue analysis seems to be capable of more accurate investigation of stability, compared with other methods like the Bode plots and the Nyquist diagrams [31].

The obvious drawback is that the method requires the state matrix of the investigated system, which means all the analytical models (equations) of the investigated system elements must be known. However, in order to protect the intellectual property of the wind turbine manufacturers, the detailed WPP models are generally provided as black-box EMT models. These models are not very suitable for the formulation of the state matrix although it is possible by using a frequency scan based on harmonic injection and a vector/matrix fitting. [11, pp. 34, 89,102] Also, in large networks the system state matrix can become large, which will increase the calculation time significantly. Thus, the eigenvalue analysis is not easily realisable when investigating subsynchronous oscillation risks in practical WPPs, however it has significant part in the theoretical investigations due to advantages mentioned above.

3.1.3 Electromagnetic transient analysis

The EMT analysis provides the precise time domain response of the WPPs. Thus, the EMT analysis provides more precise information on the frequency and damping of the subsynchronous oscillations, and how the WPP behaves during the fault conditions. Also, the detailed EMT models show how the protections of the WPP work, and if the WPP will disconnect due to the subsynchronous oscillation. [30, p. 4] The EMT analysis is also used for the validation of other methods such as the eigenvalue analysis [5] [22]. Due to the limits of simulation software and unreasonable simulation times of large network, only a small portion of the investigated network can be represented as it is. Thus, the study area should be carefully chosen and the boundary buses have to be modelled with equivalent voltage sources presenting the rest of the network. All other dynamic models and passive elements in the study area should also be included.

A drawback of the EMT analysis is that the simulation time can be rather long, especially on larger networks, as the simulation time step needs to be quite small due to the modelling of the wind turbine power converters. Thus, in order to save significant amount of time, method like frequency scanning analysis should be used first to figure out the critical conditions, which then should be investigated more with EMT analysis [30, p. 4]. The precise EMT models of the WPPs should be provided by the turbine manufacturers. Fingrid nowadays requires these models from all power plants with rated power over 60 MW connected in the vicinity of the series compensated network with a power electronics converter [8].

3.2 Mitigation methods of subsynchronous oscillations

The mitigation methods against subsynchronous oscillations can be broadly divided into three categories. The first category presented in Section 3.2.1 is the mitigation method based on converter controllers, where the power electronics converters in Type-3 and Type-4 WPPs are utilized for subsynchronous oscillation mitigation. The second category presented in Section 3.2.2 includes mitigation methods based on additional external devices such as flexible ac transmission systems (FACTS) devices. The third category presented in Section 3.2.3 is based on bypassing the series capacitor or disconnecting the WPPs at appropriate times.

3.2.1 Converter controllers

The converter-based methods are generally implemented by adding a supplementary damping controller that modulates one or more control signals of the converter control loops, according to one or more measured signals. Additionally, an adaptive controller, capable of changing the parameters of the converter, depending on the status of the network could be used. These methods are cheaper and quicker to implement compared with methods that require additional hardware investments, such as FACTS devices, and thus methods based on the converter controller are economically preferable [32, p. 419]. It is also noted that the Type-3 wind turbine converters are just as capable in W-SSCI mitigation as FACTS devices such as static synchronous compensator (STATCOM) [2, p. 1024].

In Type-3 wind turbines, many different measured and modulated signals used in the damping controllers have been investigated. Although the RSC has most impact on the damping ability of the Type-3 wind turbine, the mitigation of W-SSCI through GSC is favoured [2, p. 1024]. For instance, in [33] the electrical power as measured signal and the GSC inner control loop output as the modulated signal are found to be effective in W-SSCI damping.

In [34], a simple damping controller with voltage over the series capacitor as the measured signal and either of the GSC outer control loop outputs as the modulated signal seems to be efficient in damping W-SSCI, which has been further improved and validated recently in [35]. However, the voltage over the capacitor is a remote measurement which could be difficult to obtain fast and reliably. In [34] the voltage over the series capacitor is estimated using the local line current, however this estimation is possible in case where only the WPP is radially connected to the series capacitor, and not feasible in highly meshed series compensated network such as the Finnish transmission network.

A drawback with the aforementioned Type-3 wind turbine damping controllers is that they are generally not robust towards operation condition changes [36, p. 1718]. Improved damping in changing operation conditions can be achieved using adaptive damping controllers that use for example multiple-model adaptive control (MMAC) [36] or active disturbance rejection control (ADRC) [37]. Tuning the converter controller parameters to mitigate the W-SSCI phenomena could be used without adaptive control capability, however the controllers already have a wide range of design requirements concerning normal operation and optimizing them also to the damping of W-SSCI could be difficult or require some trade-offs with control performance. Therefore, using adaptive controls to change the performance of the converter only in exceptional situations could also be an efficient solution that takes into consideration the operation condition changes.

Regarding Type-4 wind turbines, the passivity of the wind turbines towards SSCI has resulted in lack of methods being investigated. According to [20], a Type-4 wind turbine with GSC controller using dual synchronous rotating reference frames has the advantage of low gain at all frequencies excluding the fundamental. Type-4 wind turbine with such controller is found not to be susceptible to SSCI and thus is well suitable in systems with series compensation. [20, pp. 2,5] Alternatively, positive damping of the converter could be increased with active reshaping techniques, where additional control loop in the phase-locked loop or in the GSC current control loop are used to change the impedance of the converter in subsynchronous range [38].

3.2.2 FACTS devices

FACTS devices such as the static var compensator (SVC) and STATCOM, which are generally used for fast voltage control, can also be used for subsynchronous oscillation mitigation when equipped with an additional damping controller. In fact, STATCOM is the preferred device out of all FACTS devices for mitigating subsynchronous oscillation in WPPs.

The SVC or STATCOM might already be required to implement in WPP in order to achieve the grid code requirements. In these cases, implementing the subsynchronous oscillation mitigation with SVC or STATCOM is efficient since it does not require any major additional investments. STATCOM is preferred more out of the two because it is in many ways superior to SVC. [2, pp. 1022,1024,1026]

FACTS devices related to series compensation, such as thyristor controller series capacitor (TCSC), gate-controlled series capacitor (GCSC), and static synchronous series capacitor (SSSC) could also be used to efficiently mitigate the subsynchronous oscillations [2, pp. 1023,1024]. However, if the series capacitors have already been installed, the mitigation of subsynchronous oscillation with this equipment is not economically viable due to the large investment costs of changing the series capacitors and since there are already more cost-efficient methods available.

3.2.3 Series capacitor bypass or wind power plant disconnection

The resonance point occurs due to the series connection of the WPPs and the series capacitors. Regarding Type-3 WPPs, the W-SSCI will most likely only occur when all the significant connections are series compensated, as discussed in Section 2.4.1. Thus, it would be intuitive to bypass at least one of the series capacitors in case of undamped W-SSCI. A control algorithm for proper bypassing of a series capacitor is presented for example in [39], where the series capacitor is bypassed only if the observed subsynchronous oscillation is growing. This method requires no major investment costs, and thus it can be economically appealing.

Bypassing the series capacitor does however limit the transmission capacity of the line. This is not a problem in cases where the WPPs are left connected radially with the series compensated line, since the W-SSCI usually occurs when the wind power production level is lower. Thus, the power transmission on the line is also lower (as there is only the WPP at the end of the series compensated line) and the main benefit of the series capacitor (increased transmission capacity) is already lost and bypassing the series capacitor does not have significant effect. [39, p. 419] In these cases, bypassing the radially connected series capacitor for example according to the aforementioned algorithm would most likely be the easiest way of preventing undamped and high amplitude subsynchronous oscillation. Also, the series capacitor could simply be automatically bypassed in case of a radial connection, without any subsynchronous oscillation detection algorithm.

However, in case of when the WPP is connected for example between two series compensated lines, the power transmission in the lines can be significant even if the WPP production is lower and risk of W-SSCI is higher. In these cases, bypassing one of the series capacitors to mitigate the subsynchronous oscillations could limit the transmission capacity of the lines, which is not optimal from the system operation viewpoint. Also, bypassing the series capacitor and reconnecting it again after the oscillations are damped does not work as the oscillations would simply start again if the cause of the oscillations – WPP or network configuration – is not changed in any other way. Thus, bypassing the series capacitor in order to mitigate the subsynchronous oscillation, rather than just to protect the series capacitor, is not the most viable option especially in highly meshed networks with multiple series capacitors, such as the Finnish series compensated network.

When the output power of the Type-3 WPP is lower, the damping provided by the Type-3 wind turbines is lesser and the risk of W-SSCI is greater, as discussed in Section 2.4.4. Thus, one way to prevent the W-SSCI could be to disconnect the WPP or one of the series capacitors when the output power is at certain range. However, this would again limit the transmission capacity or increase the costs due to the limiting of wind power production while the W-SSCI could still appear on higher output power. A mitigation method that would work when the W-SSCI appears and the output power is greater would still be needed. Thus, investing in a method that works regardless of the output power should still be a more viable option. As these undamped subsynchronous oscillation phenomena can cause high amplitude oscillations quickly, possibly in less than 1 second, any mitigation method manually performed by an operator is not realistic.

Disconnecting the Type-3 WPP by protection relays when undamped oscillations occur is an efficient way to dampen the oscillations. However, disconnection of the WPP removes the wind power production capacity from the system, thus it is not the most viable option to be used by itself. Methods that increase the damping of the system, such as the methods based on the converter controllers or FACTS devices should be implemented in order to prevent or reduce the number of any undamped subsynchronous oscillation phenomena and disconnection of wind power production. However, the series capacitors and WPPs should generally have protection functionalities as a backup if the damping is not sufficient for the possible subsynchronous oscillations.

3.3 Real-world events and findings

There have been numerous cases of undamped subsynchronous oscillation where the oscillations have been caused by series capacitors and WPPs, published in the past ten years or so. In Table 1 some of the findings in reported real-life cases that include the Type-3 or Type-4 WPPs, and series capacitors are presented. It should be noted that most likely not all real-world events are actually published.

In Table 1 all reported cases in series compensated networks have Type-3 WPPs. However, there seems to be no cases reported where the Type-4 WPP would have been the major cause of undamped subsynchronous oscillation in series compensated network, although Type-4 WPPs were part of oscillations in some events.

The first two items in Table 1 happened in the USA. The first item in South Central Minnesota, 2007, a WPP and a conventional turbo generation unit were left radially connected to the rest of the network with a series compensated line due to a regular switching event, which lead to undamped high amplitude currents that ultimately caused some damages in the wind turbines and in the busbar near the conventional turbo generation unit. The second item in Texas, 2009, a Type-3 WPP was also left radially connected to the network with series compensated line after a fault occurred in the adjacent uncompensated line, which resulted in damages in the Type-3 wind turbine crowbar circuit and in series capacitor. The most interesting finding in the first two items is that the subsynchronous oscillation phenomena appears most prominently in the currents, which can increase rapidly to significant levels, while the voltage increase is more restrained.

The third item in Table 1 includes a total of 58 different events where WPPs had interacted with the series compensated network in Hebei Province, China, in 2012 and 2013. The connection point of WPPs had four series compensated connections in 500 kV level to the rest of the network, and all the subsynchronous oscillation events happened when all the series capacitors were online. If even one of the series capacitors were bypassed during a subsynchronous oscillation event, the oscillations were fully damped. From the third item it should be noted that the frequency of the oscillations varied during the event mostly due to the changing number of online Type-3 wind turbines, the Type-4 WPPs behaved rather passively, and all the connected series capacitors were required for the undamped oscillations to appear. Also, the events happened mostly when the output power of the WPPs was low compared with the rated capacity, which shows that the damping of the Type-3 WPPs is worse at lower output powers, as is discussed in Section 2.4.4.

The fourth item includes a total of three different events that occurred close to the location in the second item, although the series compensated line and the WPPs in this fourth item are different. In all of the events the WPPs were left radially connected with the series capacitors. The most interesting finding from the fourth item is that the undamped subsynchronous oscillations occurred even though damping controllers had been implemented previously, and the effectiveness of the mitigation had been validated. However, numerous deficiencies in the WPP models were found, as some problems became visible only when all the nearby WPPs were modelled in full detail. This indicates that the whole nearby system should be accurately modelled in order to investigate the stability of all WPPs.

The frequencies of subsynchronous oscillation in real-world events have been observed in wide range from 6 Hz to around 30 Hz.

Table 1: Some real-world subsynchronous oscillation cases in Type-3 and Type-4 WPPs including series capacitors

Year	Location	Turbine Type	Event findings	Ref
2007	South Central Minnesota, USA	Type-3	- oscillations happened when the WPP and conventional turbo generator were left radially connected to a series compensated line due to normal switching operation - increased and distorted WPP phase current peaks from 100 A to 1000 A in 0.3 seconds, voltage increase to 1.08 pu - oscillations in 9.44 Hz frequency, which is different from the modal frequencies of the turbo generator shafts –> Type-3 WPP was the main cause of the oscillations - damages in wind turbines and in the busbar near the conventional turbo generator	[11] [40]
2009	Texas, USA	Type-3	- radial connection of WPP and series compensated line with effective 75 % compensation level	[11] [41]

			- increased and distorted currents over 300 % of normal in 0.4 seconds - oscillations around 20–30 Hz - damages in both series capacitors and wind turbine crow-bar circuits	
2012 - 2013	Hebei Province, China	mostly Type-3, also some Type-4	- during the time 58 events were captured where subsynchronous oscillations were detected, WPPs were connected with several series compensated lines - subsynchronous currents at the same level of magnitude as the fundamental current were observed in the high voltage side - Individual lines had compensation levels around 40 %. The effective compensation level seen by the WPPs was only 6.67 %. Events happened mostly when all the series capacitors were in service and the output power of the WPPs were 2.6–10.5 % of total capacity - oscillations of 6~8 Hz were observed, and the frequency changed even during the event, mostly due to the changing number of online wind turbines (part of the Type-3 wind turbines were disconnected during the events) - RSC of the Type-3 WPP found to have major impact, Type-4 WPPs behaved passively (oscillatory power less than 5 %, while Type-3 WPP had around 50 %)	[3] [18]
2017	Texas, USA	Type-3	- total of three events were detected, even though all WPPs had subsynchronous oscillation mitigation damping controllers - oscillations happened due to the radial connection of Type-3 WPP and series capacitor, the frequency of the oscillations was within 20–30 Hz, similar to the 2009 case - numerous deficiencies were found in the models, and it was found that the models only showed certain problems when all of the nearby WPPs were modelled in full detail.	[11]

4. FUTURE SCENARIOS

The Finnish transmission system is shown in Figure 4. In this thesis, the focus will be on the series compensated part of the 400 kV transmission system, which is highlighted in Figure 4 for the year 2020. In the near future, the number of wind power plants in Finland will increase significantly and the consumption of electricity will rise. Large network investments are thus also being planned and made in order to increase the transmission capabilities of the network and enable the connections of large amounts of wind power. There are three future scenarios that will be investigated in this thesis, representing the near future system, the future system and the more distant future system which approximately represent the network in end of years 2022, 2027 and 2030. The representation of the 400 kV series compensated part of the Finnish transmission system is presented in Appendix C, for the three future scenarios.

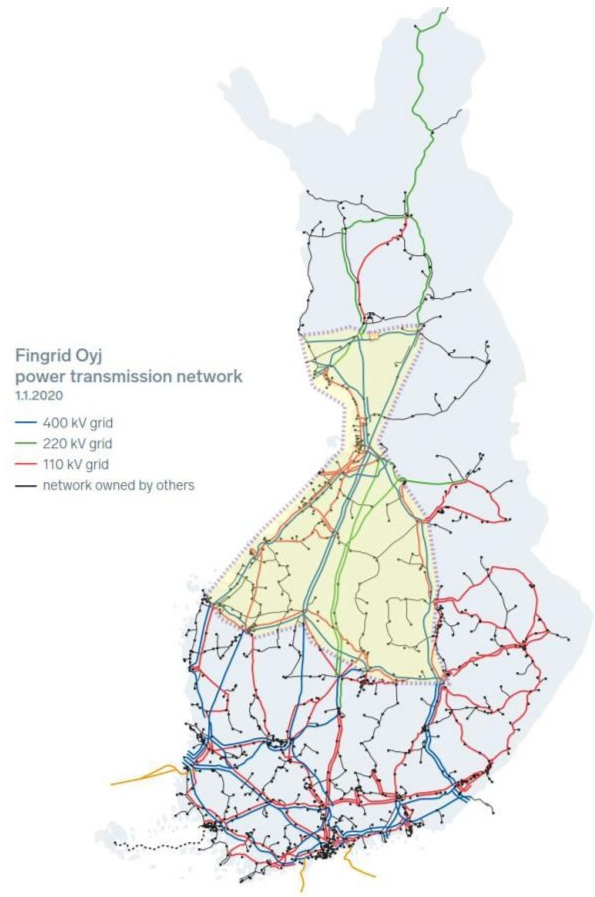

Figure 4: Finnish transmission network in 2020, with the series compensated part of the network highlighted [8]

The future scenarios are investigated by looking at certain 400/110 kV substations that are in the vicinity of the series compensated part of the Finnish transmission system highlighted in Figure 4. There are 20, 23 and 25 investigated substations in scenarios 2022, 2027 and 2030, respectively. Only the substations with wind power production in any of the future scenarios are chosen to the investigations. The amount of wind power production capacity connected to each investigated substation and in each scenario are presented next.

The estimated amount of total wind power production capacity of each wind turbine type connected to each investigated substation in different scenarios is presented in Figure 5. The amount of wind power production capacity presented in the figure consists of WPPs connected directly to the 110 kV or 400 kV buses of the substation, as well as the WPPs connected along the 110 kV transmission lines that are connected to the 110 kV bus of the substation.

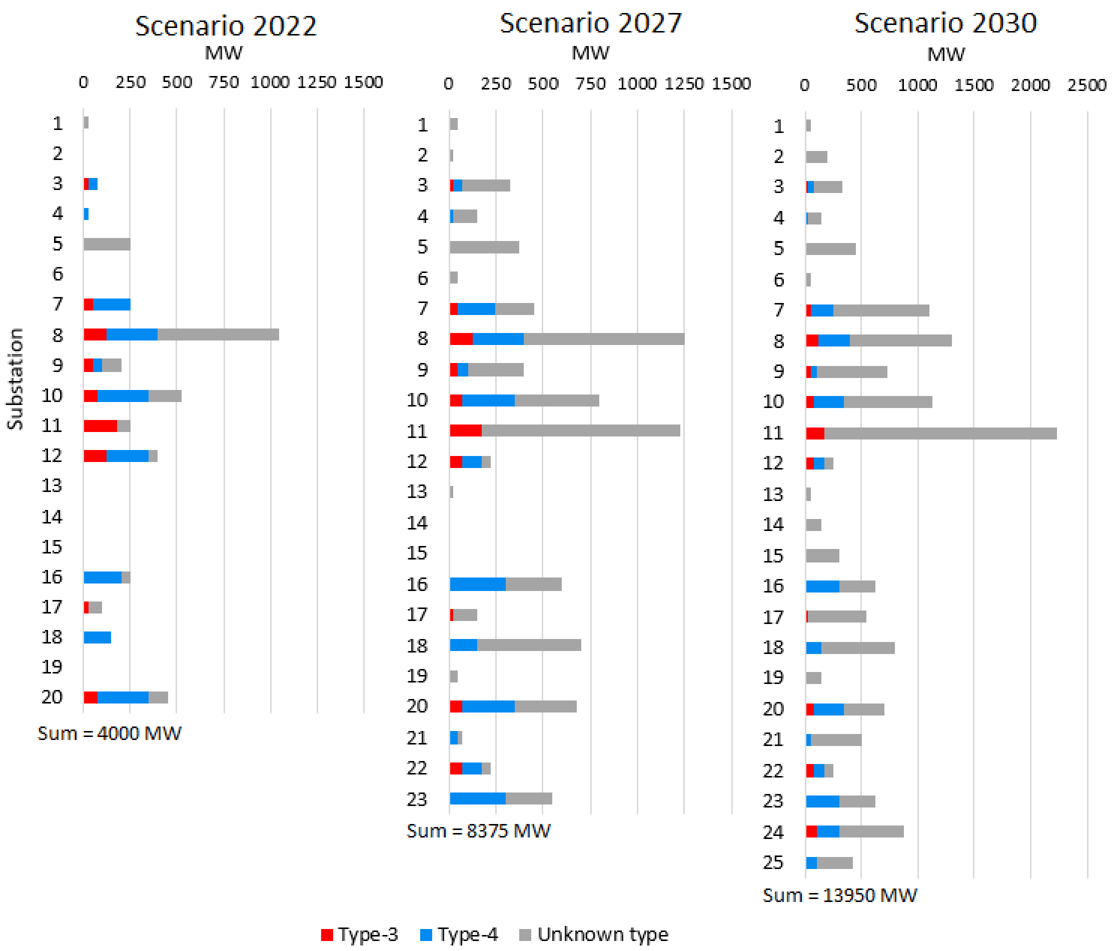

Figure 5: The total wind power production capacity and the share of each wind turbine type in all investigated substations and future scenarios

According to present requirements [8] set by Fingrid, the power electronics converter connected power plants with rated output higher than 60 MW are required to provide the PSCAD model of the WPP as well as the dynamic impedance scans, if the power plant is connected in the area highlighted in Figure 4. The impedance scans and the PSCAD model are then evaluated by the Fingrid and if a risk for undamped interactions is found in the connection point, the damping of the power plant must be improved. However, it is not specified in the requirements if the damping of the WPP with rated power over 60 MW has to be positive, only that the damping has to be satisfactory considering the connection point. Therefore, the Type-3 WPP with rated power over 60 MW can be considered not to provide significant amount of negative damping.

Thus, it is important to investigate the amount of wind power production capacity from the WPPs with rated power of 60 MW or less, because these WPPs at present do not have the requirements for the damping of subsynchronous oscillations. Especially the Type-3 WPPs with rated power of 60 MW or less have higher risk to cause W-SSCI and disconnect from the network compared to other WPPs, due to the possible high negative damping in the subsynchronous frequency range, if the requirements are not changed. Considering only the WPPs with rated power of 60 MW or less, the estimated amount of wind power production capacity of each wind turbine type connected to each investigated substation in different future scenarios is presented in Figure 5

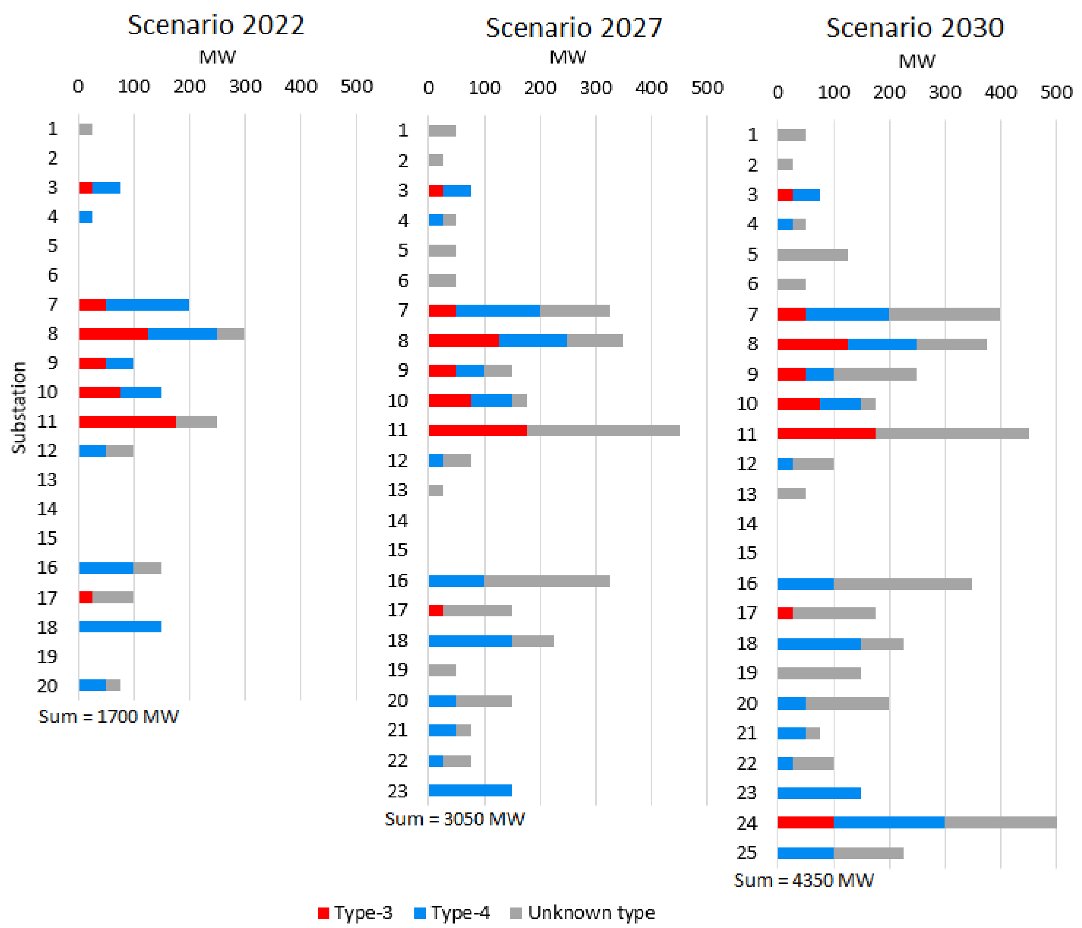

Figure 6: The wind power production capacity and the share of each wind turbine type in all investigated substations and future scenarios, considering only the WPPs with rated power of 60 MW or less.

The ratio of wind power production capacity from the Type-3 and Type-4 WPPs in the Fingrid system according to all the known in service and planned WPPs is currently roughly 1:2. In other words, roughly 33 % of all wind power production capacity is from Type-3 WPPs and 67 % are from Type-4 WPPs. As it can be seen from Figure 5 and Figure 6, the amount of wind power production capacity from the WPPs with unknown wind turbine type is significant. Therefore, investigating different Type-3 to Type-4 ratios in the future scenarios is essential.

The wind power production capacity estimates in the scenarios include all known and potential WPPs that are connected and might be connected that year. The WPPs included in the data are in many different stages of planning, and the real amount of connected wind power production capacity is in a long run dependent on how the consumption of electricity changes in Finland. Therefore, these estimations could be considered as approximate maximum amounts of wind power production capacity that could be connected to the investigated substations.

The data used to create Figure 5 and Figure 6 is presented in Appendix A.

5. SIMULATION AND RESEARCH METHODS

In Section 5.1 the PSCAD benchmark model and the used WPP models are presented. Section 5.2 presents the research methods used to investigate the amount of potentially disconnecting wind power production capacity due subsynchronous oscillations in the Finnish transmission system, as well as the simulation methods used to investigate the immunity of the manufacturer Type-4 WPP model and sensitivity of the Type-3 WPP model to the subsynchronous oscillation phenomena.

Section 5.3 presents the methods developed for validating the need and functionality of the subsynchronous oscillation protections in the Type-4 and Type-3 wind turbines, which provide an answer for the research question number two: “How the need and the functionality of the subsynchronous oscillation protections could be validated for different wind turbines”.

5.1 PSCAD model

The simulations in this thesis are done using the PSCAD software. In this thesis a single benchmark model is designed and is used for all simulations. The representation of the benchmark model is shown in Figure 7, which presents the configuration of the model as well as the essential parameters and values that are constant in all of the simulations. All constant values and parameters of the components are presented in Appendix B. The values and parameters that are varied in the simulations, as well as any additions and changes to the model, are presented in Section in 5.2 and Section 5.3 that describe the performed simulations in detail.

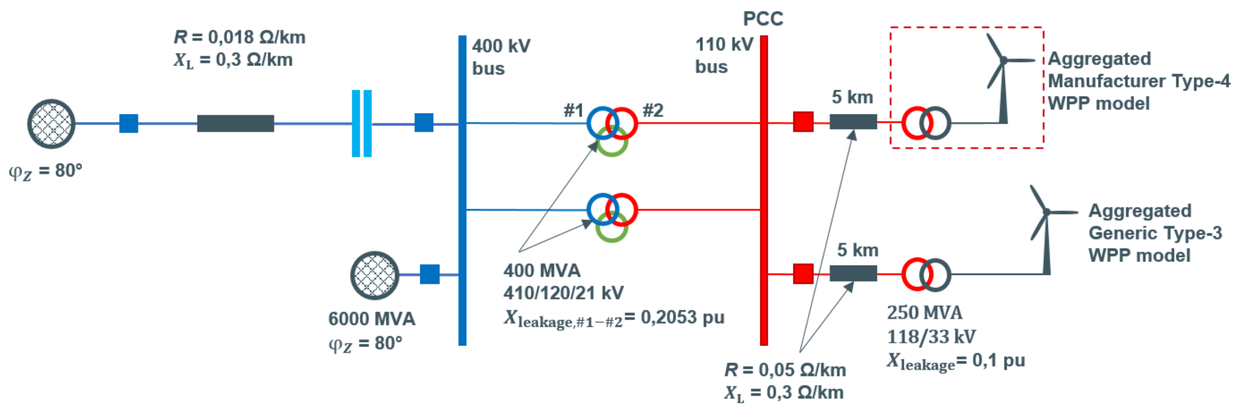

Figure 7: PSCAD benchmark model and the constant model parameters.

The benchmark model has one 400 kV bus and one 110 kV bus, and the rest of the network is modelled as a voltage source with an impedance. The resistance R_{source} and inductance L_{source} of the voltage sources are calculated according to the desired equivalent voltage source strength S, according to:

$$R_{\text{source}} = \cos(\varphi_{\text{Z}})\frac{(U_{\text{b}})^2}{S} \tag{7}$$

$$L_{\text{source}} = \frac{\sin(\varphi_{\text{Z}})\frac{(U_{\text{b}})^2}{S}}{2\pi f_0} \tag{8}$$

Where the φ_{Z} is the phase angle of the voltage source impedance and U_{b} is the nominal voltage of the equivalent voltage source. The phase angle of the voltage source impedance is in all simulations 80 degrees, and the system nominal frequency is 50 Hz. The R, X_{L} and X_{leakage} in Figure 7 are the values: resistance and inductive reactance of the transmission lines, and the leakage reactance of the transformers, respectively.

The series capacitors are modelled as ideal capacitance C_{L} in each phase, calculated according to:

$$C_{\text{L}} = \frac{1}{2\pi f l X_{\text{L}} k} \tag{9}$$

Where l is the length (km) and X_{L} is the inductive reactance (Ω/km) of the transmission line that has the series capacitor and k is the series compensation level of the transmission line.

The WPPs connect to the 110 kV bus with short connection lines of 5 km, in order to get conservative results. In reality the connection lines may generally be longer than 5 km. The 110 kV bus is defined here as the point of common coupling (PCC) for the connected WPPs. The 400 kV and 110 kV transmission lines are modelled as PI sections.

In the Finnish transmission system, the maximum amount of production capacity allowed for a single connection in a 110 kV bus of the 400/110 kV substation is less than 250 MW [42, p. 4]. The two aggregated WPPs shown in Figure 7 both represent a group of WPPs of the same type.

The rated power of the aggregated WPPs will change in some of the simulations. If the aggregated WPP rated power is equal to or greater than 250 MW, additional connection lines and connection transformers are added in parallel to simulate the multiple connection lines. For each 250 MW of rated wind power production capacity, there is one transmission line and one connection transformer connected. The values presented in Figure 7 represent the values of single connection line and single connection transformer.

However, the medium and low voltage networks in the WPPs are not modelled in any of the WPP models, therefore those are not considered in the aggregated models either.

The WPPs with equal to or higher rated power than 250 MW are connected to the 400 kV level. However, since WPPs of this size most likely also have 110 kV or similar collection network, the simulation model for WPP connected to 400 kV bus would become similar to the model in Figure 8 where there are multiple smaller WPPs connected to the 110 kV side. Thus, only the model where the WPPs are connected to the 110 kV bus is used.

The normal voltage in the 110 kV bus is 118 kV, and in the 400 kV bus it is 410 kV, which are defined as normal connection point voltages in the Finnish transmission system [42, p. 8]. As the 110 kV bus is the PCC, the voltage controls in the WPPs adjust the voltage in this point. The positions of the tap-changers of all the transformers in the model are kept constant in all simulations. Any additional compensation units in the WPPs are not included in the WPP models, only the wind turbines themselves.

The possibility for subsynchronous oscillations is created with the benchmark model by disconnecting the network equivalent that is not connected to the 400 kV bus with a series compensated line, so that the WPPs are left connected in series with the series capacitor. This is the simplest network topology that causes a risk for subsynchronous oscillations. It can also be considered as the topology with the greatest risk of subsynchronous oscillations, as the damping provided by the network is less than compared to topologies with additional network connections in the 400 kV or 110 kV busses.

With this simple model, the subsynchronous oscillation damping abilities of the WPPs and the behaviour of the WPPs during possible subsynchronous oscillations can be investigated, which are the main focus in this thesis. However, the risk of subsynchronous oscillations for example in different network topologies cannot be investigated with the benchmark model presented above. The benchmark model above thus represents for example a substation in a middle of a long series compensated transmission line, where the substation is left radially connected to the rest of the network through a series compensated transmission line after the other connection is removed.

The wind power plant models used in the simulations include a detailed model provided by a wind turbine manufacturer, as well as generic wind turbine models. One detailed Type-4 WPP model, provided by a Type-4 wind turbine manufacturer is used. Unfortunately, a manufacturer model of a Type-3 WPP with sufficient accuracy could not be acquired for simulations. Therefore, two generic Type-3 WPP models are used, one more detailed model [43] and one less detailed [44]. The major difference between these models is that in the more detailed model the firing controls of the insulated gate bipolar transistor (IGBT) switching is modelled in full detail at the wind turbine converter model. As mentioned in Section 2.2, the subsynchronous oscillation phenomena in Type-3 wind turbines is mostly affected by the induction generator and the converter controls, therefore a model including the firing controls of the transistors is not necessarily required. However, the fact that the less detailed Type-3 WPP model does not have the voltage control functionality implemented and other available less detailed Type-3 WPP model was not numerically stable in the benchmark model, lead to the use of the detailed Type-3 WPP model in majority of the simulations.

5.2 Investigation on the disconnecting wind power production capacity

5.2.1 Disconnecting production capacity in future scenarios

In this investigation, the scenarios for future Finnish transmission network presented in Chapter 4 are investigated. In the investigation it is assumed that the WPPs that are disconnected due to the subsynchronous oscillations are operating at the rated power (i.e. production capacity). The objective is to estimate the amount of disconnected wind power production capacity at each investigated substation due to the subsynchronous oscillation. The analysis will provide an answer for the research question number one: "What is the greatest amount of potentially disconnecting wind power production capacity due to the undamped subsynchronous oscillation phenomena in the different future scenarios of the Finnish series compensated transmission network, and what are the critical locations?"

It is assumed that the possible subsynchronous oscillation phenomena are limited to only single substation. The damping provided by the 400 kV lines between the substations – even in case of relatively close by substations – is considered sufficient in damping the oscillations, which should prevent the disconnection of WPPs at adjacent substation before the WPPs in the cause substation are disconnected and the phenomena disappears. However, the assumption that the risk of oscillations does not appear in multiple substations at the same time cannot be validated with the data presented in Chapter 4, and should be investigated thoroughly in the future.

It is also assumed that only Type-3 wind turbines have a risk of disconnecting due to the undamped subsynchronous oscillations. According to the literature and real-world events discussed in Section 2.3.2 and Section 3.3 respectively, the Type-4 wind turbines can be considered not to cause undamped SSCI by themselves. The Type-4 WPPs can be exposed to high voltages due to W-SSCI caused by any nearby Type-3 wind turbines, however due to the passivity of the Type-4 wind turbines the wind turbine subsynchronous oscillation protections of the Type-3 wind turbines most likely are tripped way before there is need for the Type-4 wind turbines to disconnect.

A single manufacturer Type-4 WPP model is also investigated to verify the assumptions made above, and these investigations as well as the results of the investigations are presented in Sections 5.2.2 and 6.2, respectively.

As explained in Chapter 4 the Type-3 WPPs with rated power of 60 MW or less could have high negative damping due to the lack of subsynchronous oscillation damping requirements. Therefore, it can be considered more likely that the Type-3 WPPs with rated power of 60 MW or less are the main cause of the undamped W-SSCI, and therefore are also assumed to be exposed to higher amplitude current and voltage oscillations in the wind turbines' terminals. This assumption should however also be investigated thoroughly in the future.

However, the Type-3 WPPs with rated power over 60 MW cannot be assumed to behave passively during any undamped W-SSCI caused by Type-3 WPPs with rated power of 60 MW or less. Therefore, it is still possible that all the Type-3 WPPs are disconnected in case of undamped W-SSCI in a worst-case scenario.

Next, the research method used to estimate the amount of potentially disconnecting amount of wind power production capacity is presented. Due to the assumptions mentioned above, the amount of potentially disconnecting wind power production capacity is defined in two cases in order to analyse the sensitivity of the assumptions:

- In a conservative case, it is assumed that all the Type-3 wind power production capacity connected to the investigated substation will disconnect.
- In a more reasonable case only the wind power production capacity from the Type-3 WPPs with rated power of 60 MW or less will disconnect.

This sensitivity analysis is also conducted in order to observe if there is a need to change the 60 MW limit in the damping requirements. These production capacity amounts are presented in Chapter 4 and in Appendix A.

However, as it can be seen from Figure 5 and Figure 6, a significant amount of the estimated wind power production capacity is from WPPs with unknown wind turbine type. The unknown wind power production capacity needs to be first shared for Type-3 and Type-4 turbine types. As mentioned in Chapter 4, the Type-3 to Type-4 ratio of the wind turbine production capacity in the Finnish transmission system is roughly 1:2 according to existing and planned WPPs in Fingrid's database. As it is difficult to predict the share of the wind turbine types in the future, a sensitivity analysis is also performed to the Type-3 to Type-4 ratio. Three different ratios will be used in this study: 1:2, 2:1 and 1:0. The first two ratios provide a more realistic scenarios, while the third ratio represents a case where all the unknown wind power production capacity in a substation happens to be from Type-3 WPPs. Thus, the amount of wind power production capacity from Type-3 WPPs in the investigated substations is defined by the sum of the known capacity and the capacity calculated from the unknown type WPPs using the aforementioned ratio.

The five substations with the highest amount of potentially disconnecting wind power production capacity in different future scenarios are presented. The greatest amount of potentially disconnecting wind power production capacity in any of the investigated substations is then presented, considering the sensitivity analysis performed on the Type-3 to Type-4 ratio.

5.2.2 Immunity of the Type-4 wind turbines

As mentioned in Section 2.3.2, the Type-4 wind turbines are generally considered to not cause any undamped SSCI and behave passively when exposed to oscillations created by the nearby Type-3 WPPs. These assumptions are also made in Chapter 4 when estimating the maximum amount of potentially disconnecting wind power capacity. However, these assumptions should not be assumed readily, and they should be investigated thoroughly. The simulation methods – divided into three parts – used to validate these assumptions using the manufacturer Type-4 WPP model are presented in Table 2.

Table 2: The simulations performed to investigate the manufacturer Type-4 WPP immunity to the undamped SSCI and the response of the manufacturer Type-4 WPP during W-SSCI caused by the nearby generic Type-3 WPP. The possibility of the subsynchronous oscillation phenomena is created in all simulations by opening the Equivalent B breaker (see Figure 8).

		Parameters and values
First part	**Investigation if the Type-4 WPP causes undamped SSCI** - only the investigated Type-4 WPP is connected to the PCC - a set of simulations are performed by varying the parameter values of the simulation	Table 3
Second part	**Investigation on the effect of Type-4 WPP on the damping of the subsynchronous oscillations caused by the generic Type-3 WPP** - generic type-3 WPP connected to the PCC - two simulations are performed, first with the investigated Type-4 WPP in service, and second with the investigated Type-4 WPP out-of-service	Table 4
Third part	**Investigation on the response of Type-4 WPP when exposed to high amplitude subsynchronous oscillations caused by the generic Type-3 WPP** - both the investigated Type-4 WPP and generic Type-3 WPP are connected to the PCC - a single simulation is performed	Table 5

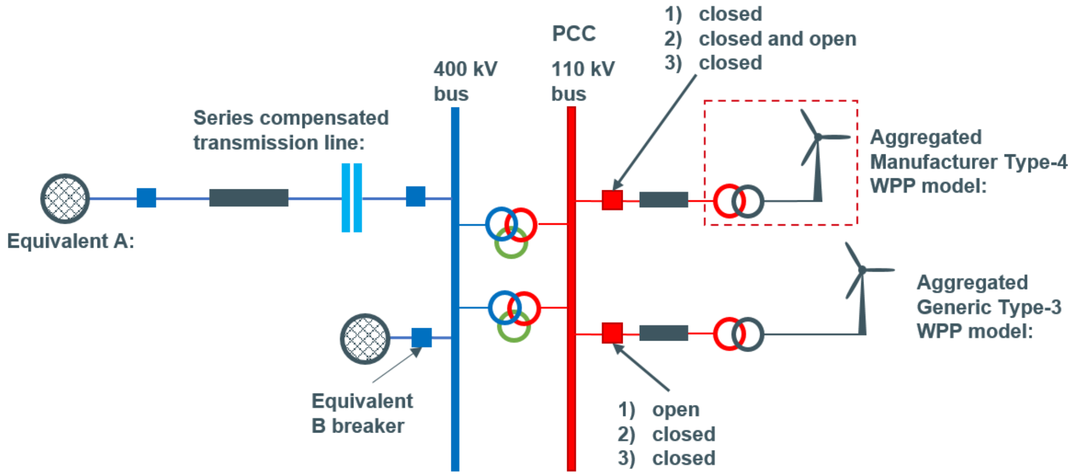

Figure 8: Benchmark model set up for the 1) investigation if the manufacturer Type-4 WPP causes undamped SSCI, 2) investigation on the effect of manufacturer Type-4 WPP on the damping of the subsynchronous oscillations caused by the generic Type-3 WPP, and 3) investigation on the response of manufacturer Type-4 WPP when exposed to high amplitude oscillations caused by the generic Type-3 WPP

In the first part of the investigations, it is inspected if the investigated Type-4 WPP causes undamped SSCI in Finnish series compensated transmission network. The benchmark model that is used is presented in Figure 8.

To see if the investigated Type-4 WPP is susceptible to undamped SSCI, only the investigated Type-4 WPP is connected to the PCC, and a series resonance point is created in the subsynchronous frequency range by opening the Equivalent B breaker (see Figure 8). The possibility for Type-4 WPP to interact with series compensated branch is assessed by observing the output current of the Type-4 WPP. A simulation sequence (a set of simulation runs) is designed to represent the different realistic operation conditions in the Finnish series compensated transmission network. The parameters that are varied in the simulation sequence are the following:

- series compensation level of series compensated transmission line
- length of series compensated transmission line
- strength of Equivalent A (see Figure 8)
- wind speed
- voltage control reference value of investigated Type-4 WPP
- rated output of the investigated Type-4 WPP

The varied values of the parameters listed above are presented in Table 3. All the combinations of different parameter values are simulated in the simulation sequence. As the Type-4 WPP voltage control reference is the only value to be changed during the simulations runs, the number of individual simulation runs in the simulation sequence is 630. The rated power of the WPP is varied by changing the number of wind turbines, while the rated power of a single turbine is the same in all simulations.

During each run of the sequence the 5–45 Hz current magnitude as well as the instantaneous phase voltages of the PCC are measured in order to identify possible undamped oscillations. In steady state operation, the 5–45 Hz current magnitude is close to zero, but if undamped subsynchronous oscillations occur the current will increase considerably. The 5–45 Hz current will also increase during different events such as opening the Equivalent B breaker or changing the voltage reference value, hence the current is measured only after a short moment (at least 2 seconds) of performing these events, giving time for the WPP to reach steady state if the SSCI is well damped.

Table 3: Varied parameters and their fixed or varied values used in the first part of the investigation, where the immunity of the manufacturer Type-4 WPP to cause SSCI after Equivalent B (in Figure 8) is disconnected from the system is investigated for all combinations of the presented parameters.

Parameter	Values
Fixed during simulation run	
Series compensation level of the 400 kV transmission line, [%]	25, 35, 45, 55, 65, 75, 85
400 kV transmission line length, [km]	100, 200
Equivalent A strength, [MVA]	4000, 6000, 8000, 10000, 12000
Wind speed, [m/s]	4, 8, 12
WPP rated output [MW]	100, 300, 600
Varied during simulation run	
WPP V-control reference value, [pu]	0.9; 1; 1.1

In the second part of the investigation, the effect of the manufacturer Type-4 WPP on the damping of the subsynchronous oscillations is investigated. The investigation is performed in a single case of the benchmark model presented in Figure 8, and the parameters and values of the case are shown in Table 4.

To see the effect of the manufacturer Type-4 WPP on the damping of subsynchronous oscillations, the simulation is run two times: First with the investigated Type-4 WPP in service and second with the Type-4 WPP out-of-service. In both simulation the Type-3 WPP causes undamped subsynchronous oscillations after the Equivalent B breaker (see Figure 8) is opened. The connection line of the generic Type-3 WPP has additional damping added in order to more clearly show the effect of the manufacturer Type-4 WPP. The additional damping is added so that the oscillations caused by the generic Type-3 WPP are barely undamped when the manufacturer Type-4 WPP model is in service. The amount of damping added is roughly equal to damping from additional 30 km of the same 110 kV connection line. Additional damping was added as pure resistance instead of a connection line length increase, in order to not change the frequency of the oscillations.

The difference in the Type-3 WPP output current between the two simulation runs is observed and analysed, in order to observe the damping provided by the manufacturer Type-4 WPP on the subsynchronous oscillations.

Table 4: Parameters and their values used in the second part of the investigation where the damping of the subsynchronous oscillations, caused by the generic Type-3 WPP after the Equivalent B breaker (see Figure 8) is opened, is observed when the investigated Type-4 WPP is in service and out-of-service.

Parameter	Value
Series compensation level of the 400 kV transmission line, [%]	85
400 kV transmission line length, [km]	200
Equivalent A strength, [MVA]	12000
Wind speed, [m/s]	12
Type-4 WPP V-control reference value, [pu]	1
Type-3 WPP V-control reference value, [pu]	1
Type-4 WPP rated output [MW]	100
Type-3 WPP rated output [MW]	300
Additional damping (resistance) in the Type-3 WPP connection line [Ω]	1.47

In the third part of the simulations, the response of the manufacturer Type-4 WPP when exposed to high amplitude subsynchronous oscillations caused by the generic Type-3 WPP is investigated. The investigation is performed in a single case of the benchmark model presented in Figure 8, and the parameters and values of the case are shown in Table 5.

To see the response of the manufacturer Type-4 WPP during the oscillations caused by the generic Type-3 WPP, the simulation is run with the parameters presented in Table 5. The parameters of the simulation are the same as the parameters used in the second part of the simulations presented above, except that the Type-3 WPP connection line does not have the additional damping added.

The difference between the Type-3 WPP output current and Type-4 WPP output current at PCC is observed when the Type-3 WPP causes undamped W-SSCI after the Equivalent B breaker (see Figure 8) is disconnected.

Table 5: Parameters and their values used in the third part of the investigation, where the response of manufacturer Type-4 WPP during the subsynchronous oscillations, caused by the generic Type-3 WPP when the Equivalent B (see Figure 8) is disconnected from the system, is investigated.

Parameter	Value
Series compensation level of the 400 kV transmission line, [%]	85
400 kV transmission line length, [km]	200
Equivalent A strength, [MVA]	12000
Wind speed, [m/s]	12
Type-4 WPP V-control reference value, [pu]	1
Type-3 WPP V-control reference value, [pu]	1
Type-4 WPP rated output [MW]	100
Type-3 WPP rated output [MW]	300

5.2.3 Sensitivity of the Type-3 wind turbines

A sequence similar to one performed on the manufacturer Type-4 WPP model in the first part of the investigation presented in Section 5.2.2 is also performed to the detailed generic Type-3 WPP model. The objective of this simulation is to present how differently a generic Type-3 WPP model would perform in a similar study and see how sensitive the generic Type-3 WPP model is to cause the undamped W-SSCI. The simulation model is shown in Figure 9. The Type-3 WPP is connected to the 110 kV bus of the benchmark model presented in Figure 9, and the Type-4 WPP is out-of-service.

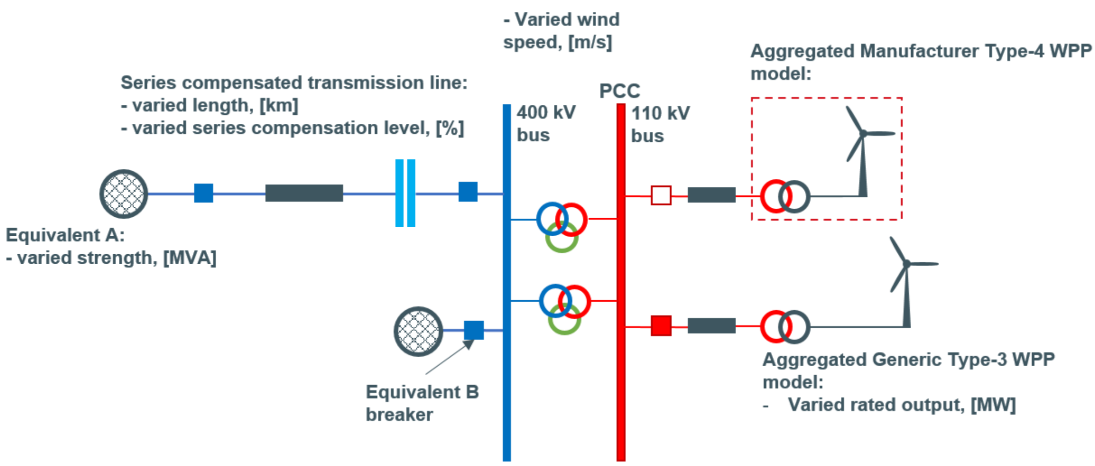

Figure 9: Benchmark model set up for the investigation of the Type-3 wind power plant sensitivity to cause undamped W-SSCI

The different values in this simulation are not varied as thoroughly as in the investigation performed on the Type-4 WPP in the first part of the investigation in Section 5.2.2. This is mostly due to fact that running as many simulations as with the detailed generic Type-3 WPP model would have taken exceedingly long time, and the same results most likely are also seen from a smaller sequence set. The varied values in the simulation sequence are presented in Table 6. Again, all the combinations of different parameter values are simulated in the sequence. The total number of simulation runs is therefore 108.

Table 6: Varied parameters and their fixed values in the simulation sequence investigating the sensitivity of the Type-3 WPP to cause W-SSCI after the Equivalent B breaker (see Figure 9) is disconnected

Parameter	Varied values
Series compensation level, [%]	25, 55, 85
400 kV transmission line length, [km]	100, 200
Equivalent A strength, [MVA]	4000, 8000, 12000
Wind speed, [m/s]	8, 12
Type-3 WPP V-control reference value, [pu]	1
Type-3 WPP rated output [MW]	50, 100, 200

5.3 Validation of the subsynchronous oscillation protections

5.3.1 Need for Type-4 wind turbine protections

The Type-4 WPPs can generally be considered immune to the SSCI phenomena and they behave relatively passively during any undamped subsynchronous oscillation caused by other nearby WPPs according to the literature and real-life events, presented in Sections 2.3.2 and 3.3 respectively. In this thesis, a method for evaluating the need of specific subsynchronous oscillation protection in Type-4 wind turbines was developed during generic studies made with the manufacturer Type-4 WPP model and in cooperation with the wind turbine manufacturer. The method consists of three steps:

1. Validating that the Type-4 WPP does not cause undamped SSCI using a simulation sequence similar to the first part of the investigation presented in Section 5.2.2
2. Defining the worst-case using a parallel connected generic Type-3 WPP
3. Discussion with the wind turbine manufacturer in order to define the need and functionality of the specific wind turbine subsynchronous oscillation protection

The objective of the first step is to make sure that the investigated Type-4 wind turbines do not cause undamped SSCI in any realistic WPP or network operation condition. The parameters and values varied in the performed simulation sequence do not need to be identical to the one presented in the first part of the investigation presented in Section 5.2.2, however the parameters and varied values should well cover realistic operation conditions in the Finnish transmission system. If the Type-4 WPP causes undamped SSCI in any of the investigated operation conditions, the specific subsynchronous oscillation protection should be added and the functionality of the protections would be validated similarly as with Type-3 WPPs presented in Section 5.3.2.

In the second step, the worst-case PCC voltage oscillations caused by the interaction between the Type-3 WPP and the series compensated network are defined, in order to simulate what the Type-4 WPP would have to be able to endure if specific subsynchronous oscillation protections were not implemented. Figure 10 and Table 7 present the study simulation model and the varied parameter values used to define the worst-case, respectively. A series resonance point in the subsynchronous range is created by opening the Equivalent B breaker (see Figure 10), which causes the generic Type-3 WPP to initiate the undamped W-SSCI.

Varied parameters and their fixed or varied values used in the first part of the investigation, where the immunity of the Type-4 WPP to cause SSCI after Equivalent B (in Figure 8) is disconnected from the system. All combinations of the different values are simulated.

Table 7: Varied parameters and their fixed values for estimating the worst-case subsynchronous voltage oscillation observed in the PCC caused by the interaction between the Type-3 WPP and the series compensated network in benchmark model presented in Figure 10.

Parameter	Varied values
Type-3 WPP rated output	100 MW, 200 MW
Series compensation level (and corresponding series capacitor protective voltage level)	25 % (113 kV), 50 % (225 kV), 85 % (286 kV)
Equivalent A strength	4000 MVA, 8000 MVA, 12000 MVA

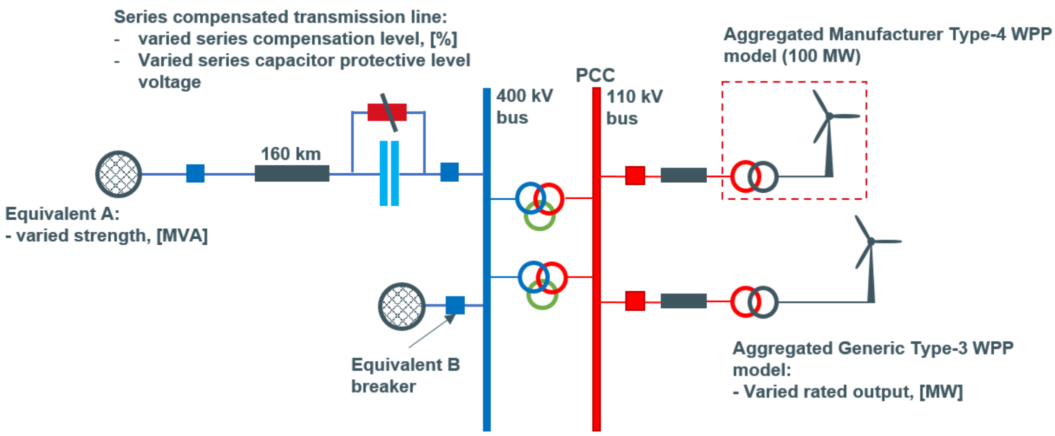

Figure 10: Study simulation model for estimating the worst-case subsynchronous voltage oscillation occurring in the PCC caused by the interaction between the Type-3 WPP model and the series compensated network

The simulation model used in this investigation and presented in Figure 10 also has the MOV of the series capacitor modelled. As explained in Section 2.5.1, the MOV of the series capacitor works as an overvoltage protection for the series capacitor and limits the subsynchronous oscillations voltages to certain level. Thus, the highest possible subsynchronous voltage component that can be observed in the 110 kV PCC is mostly defined by the protective voltage level of the series capacitor (i.e. the rated voltage of the MOV). However, the series compensation level, and therefore the capacitance of the series capacitor and the series capacitor protective voltage level, was varied in order to observe the maximum voltage oscillation magnitude in different frequencies. The maximum protective voltage levels of the series capacitor used in Finland are presented in Table 7 for three different investigated series compensation levels of the 160 km long series compensated transmission line.

The high subsynchronous currents caused by the interaction between Type-3 WPP and the series compensated network can also lead to saturation in the transformers, which can further increase the highest estimated subsynchronous voltage in the 110 kV PCC bus. The study sequence presented in Table 7 is also simulated with the saturation of the transformers turned on, to see the effect of the transformer saturation on the highest estimated PCC voltage.

The series capacitors used in the Finnish transmission system have SSO protections with a maximum pick-up time of 2 seconds [27]. Thus, if no protection would operate in the Type-3 WPPs that are causing the oscillations, after around 2 seconds the series capacitor would likely be bypassed. Therefore the 2 seconds would be the maximum time that the Type-4 WPP would have to be able to endure during the worst-case if specific subsynchronous oscillation protection is not implemented in the Type-4 WPP.

In the third step, the results from the steps described above are presented to the wind turbine manufacturer. The wind turbine manufacturer will make the final assessment if the wind turbines can endure the worst-case or not. If it is found that the wind turbine can endure the worst-case, then the investigated wind turbine should not be required to have specific subsynchronous oscillation protection functionality. However, if it is determined that the wind turbine cannot endure the worst-case, the specific subsynchronous oscillation protections have to be implemented to each wind turbine. The protections should prevent any damages in the wind turbines' components, however the wind turbine should stay connected to the grid as long as possible, because it will help prevent the unnecessary disconnection of wind power production and possibly provide positive damping to the oscillations. The functionality of the protection in these situations should be devised and validated case-by-case.

The findings from the generic study with the manufacturer Type-4 WPP model following the steps presented above are presented in Section 6.4, which ultimately lead to the investigated Type-4 wind turbine model not required to have a specific subsynchronous oscillation protection functionality.

5.3.2 Functionality of the Type-3 wind turbine protections

For Type-3 WPPs, the risk of undamped W-SSCI can be considered to be significant, according to the literature and real-life events presented in Sections 2.2 and 3.3 respectively. Therefore, the subsynchronous oscillation protections should be always implemented and validating the need of protections in Type-3 wind turbines does not have to be separately performed.

Before the protections can be validated, the desired functionality of the protections needs to be defined. However, currently the requirements do not specify how the protections should operate, only that the WPP equipment has to be protected and the protection should be implemented primarily in each wind turbine. Formulating the precise requirements for the subsynchronous oscillation protections in Type-3 WPPs was not an objective in this thesis, and thus the desired functionality of the protection is only roughly devised and proposed. The proposed functionality is presented in Section 6.5.

The method for evaluating the functionality of the subsynchronous oscillation protection in Type-3 wind turbines is presented next. The method consists of two steps:

1. Investigating the operation of the protection when injecting subsynchronous current or voltage of different magnitude and frequency to the wind turbine terminal
2. Investigating the selectivity of the protection by using another parallel connected Type-3 WPP model

In the first step, the operation of the protection is investigated by injecting subsynchronous voltage or current of certain frequency on top of the fundamental voltage or current in the wind turbine terminal. Different magnitudes of injected subsynchronous current or voltage should be investigated and the frequency should be varied in range of 5–45 Hz, in order to validate the sensitivity, speed and reliability of the protection. The three-phase currents and voltages in the wind turbine terminal should be observed and the operation time of the protection should be measured in all investigated cases. This validation should be performed at factory testing or in similar test conditions. If the PSCAD model of the wind turbine with all the relevant protection functionalities included in sufficient manner is available, the PSCAD could also be used to verify the functionality of the protection.

Validating the operation of the protection by varying the parameters presented above however only determines if the subsynchronous oscillation protection detects the undamped oscillations properly and operates in the desired operation time window. However, when there is less difference in the response between the Type-3 wind turbines, the selectivity of the protection cannot be fully guaranteed.

In the second step, in order to validate the selectivity of the protection when the difference in response between the wind turbines is small, at least one different Type-3 WPP model would be required in addition to the investigated Type-3 WPP model. Then, the WPPs would be connected in parallel at a same PCC with similar connection line, and the tripping of the wind turbines at both WPPs would be observed during undamped subsynchronous oscillations caused mainly by the other WPP. Which WPP is the major reason for the oscillations could be determined for example by acquiring the dynamic impedance scan of the WPPs and comparing the damping of the WPPs in the observed oscillation frequency. The subsynchronous oscillation protections are required to be modelled in both WPP models.

Unfortunately, a manufacturer Type-3 WPP model with sufficiently modelled wind turbine protections is not available to be used in this thesis, and therefore the method presented above cannot be tested. The desired functionality of the subsynchronous oscillation protection is however devised using the generic Type-3 WPP model, which is presented in Section 6.5.

6. RESULTS

The results in Section 6.1 will provide an answer for the research question number one: “What is the greatest amount of potentially disconnecting wind power production capacity due to the undamped subsynchronous oscillation phenomena in the different future scenarios of the Finnish series compensated transmission network, and what are the critical locations?”

The results in Section 6.2 and in Section 6.3 present the results from investigation on the immunity of the manufacturer Type-4 WPP and sensitivity of generic Type-3 WPP to subsynchronous oscillation phenomena.

The results in Section 6.4 present the findings from the study where the subsynchronous oscillation protections was investigated in the manufacturer Type-4 wind turbines using the method presented in Section 5.3.1. The results in Section 6.5 present the desired functionality of the Type-3 wind turbine protections. The desired functionality can be validated using the method presented in Section 5.3.2.

6.1 Disconnecting wind power production capacity

6.1.1 Amount of potentially disconnecting production capacity

The conservative assumption made in Section 5.2.1 is that all the Type-3 WPPs in a single substation would disconnect as a result of undamped subsynchronous oscillation phenomena. The five substations with highest amount of estimated disconnecting wind power production capacity calculated using the aforementioned conservative assumption and by varying the Type-3 to Type-4 ratio is presented in Figure 11.

The more reasonable assumption made in Section 5.2.1 is that only Type-3 WPPs with rated power of 60 MW or less will disconnect due to the undamped subsynchronous oscillation phenomena, because the subsynchronous oscillation damping requirements are not defined for WPPs with rated power of 60 MW or less. The five substations with highest amount of estimated disconnecting wind power production capacity calculated using the aforementioned more reasonable assumption and by varying the Type-3 to Type-4 ratio is presented in Figure 12.

The amount of disconnecting wind power production capacity in each substation is influenced significantly by the used Type-3 to Type-4 ratio, which is difficult to predict, and precise estimations cannot be calculated. Therefore, the maximum amount of potentially disconnecting wind power production capacity in each scenario should be defined as a range, where the minimum is defined by the highest amount of disconnecting production capacity when only considering the ratio of 1:2, and where the maximum is defined by the highest amount of production capacity when only considering the ratio of 1:0. While the ratio of 1:0 is not realistic on a scale of the whole investigated system, it is a plausible when considering a single substation. To get a conservative result, the 1:2 ratio is used as a minimum since it is the current Type-3 to Type-4 ratio considering the whole Fingrid system.

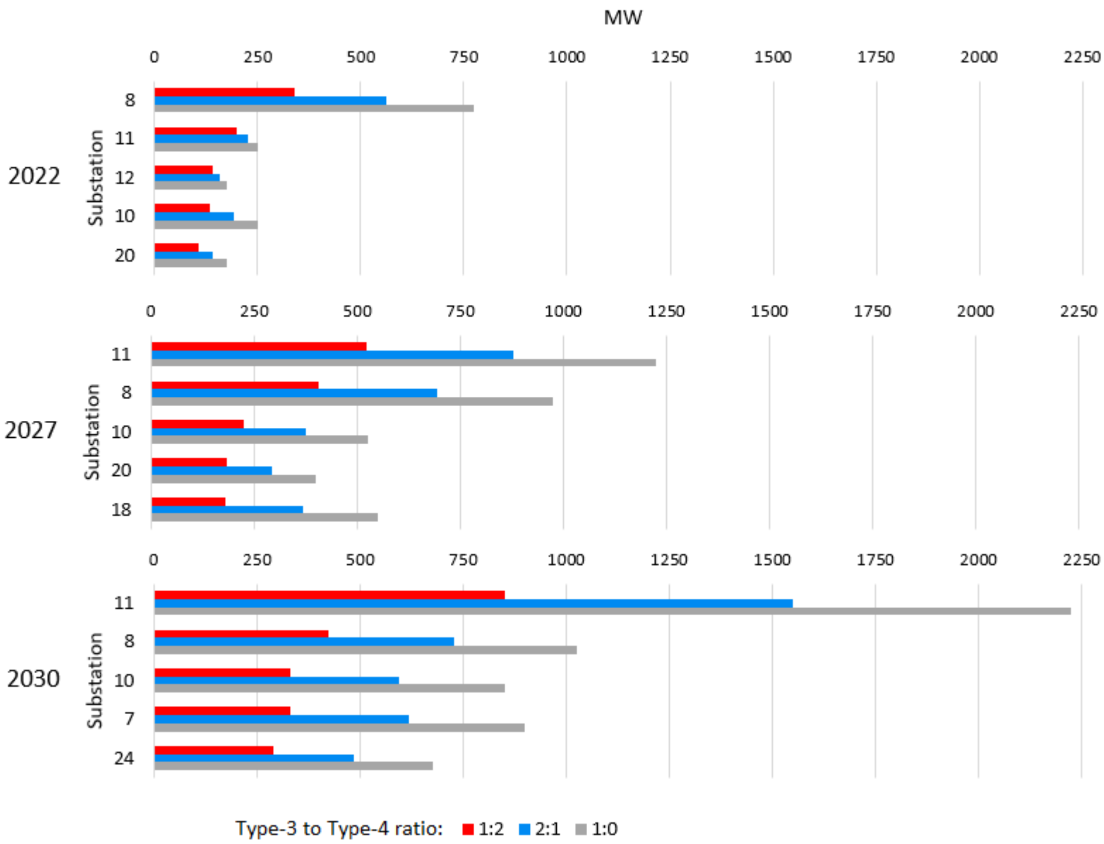

Figure 11: The amounts of estimated disconnecting wind power production capacity, calculated by using the assumption that all the WPPs with the Type-3 wind turbines will disconnect as a result of undamped subsynchronous oscillations and by varying the Type-3 to Type-4 ratio. The five substations with the most potentially disconnecting wind power capacity, considering the Type-3 to Type-4 ratio of 1:2, are presented in all future scenarios.

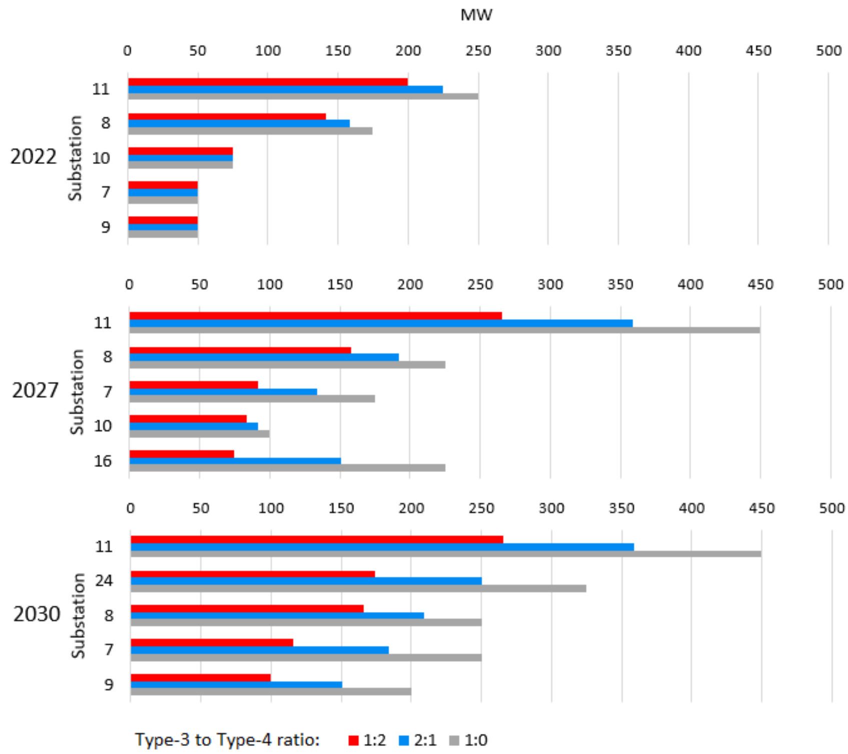

Figure 12: The amounts of estimated disconnecting wind power production capacity, calculated by using the assumption that only the WPPs with the Type-3 wind turbines and rated power of 60 MW or less will disconnect as a result of undamped subsynchronous oscillations and by varying the Type-3 to Type-4 ratio. The five substations with the most potentially disconnecting wind power capacity, considering the Type-3 to Type-4 ratio of 1:2, are presented in all future scenarios.

From Figure 11 it can be concluded that the conservative estimate for maximum amount of wind power production capacity that could potentially be disconnected due to the subsynchronous oscillation phenomena in the Finnish transmission network is in range:

- 340–775 MW in scenario 2022
- 520–1225 MW in scenario 2027
- 850–2225 MW in scenario 2030

From Figure 12 it can be concluded that the more reasonable estimate for highest amount of wind power production capacity that could potentially be disconnected due to the subsynchronous oscillation phenomena in the Finnish transmission network is in range:

- 200–250 MW for scenario 2022
- 270–450 MW in scenarios 2027 and 2030

6.1.2 Analysis of the results

First, the results presented in Figure 11 are analysed. The figure presents the amounts of estimated disconnecting wind power production capacity, calculated by using the assumption that all the WPPs with the Type-3 wind turbines will disconnect as a result of undamped subsynchronous oscillations.

As it can be seen from Figure 11 the five substations are not all the same in all of the scenarios, although the Substations 8, 10 and 11 are present in all of the scenarios. Also, while the Substation 8 is easily the substation with most wind power production capacity from Type-3 wind turbines in scenario 2022, the Substation 11 quickly takes the first place in scenarios 2027 and 2030.

Looking at the scenario for year 2022, it can be seen that there is not a great difference between the amounts of disconnecting wind power production capacity when using different Type-3 to Type-4 ratios. This means that the wind turbine types used in the WPPs estimated to be in operation in year 2022 are fairly well known. One exception is the Substation 8, where the difference between the disconnected production capacities is relatively large when using different Type-3 to Type-4 ratios. This means that there is a significant amount of wind power production capacity from WPPs that have unknown wind turbine type. These conclusions can also be seen from Figure 5. As of writing this thesis (2021) the scenario 2022 is for next year, and thus the most likely reason for the lack of information in this scenario is that the wind turbines planned for the WPPs have not been updated on the database or have not been provided by the WPP manufacturer.

Unfortunately, Substation 8 is also the substation with the most potentially disconnecting wind power production capacity in the scenario 2022, regardless of the used Type-3 to Type-4 ratio. In other words, the substation with the most uncertainty also happens to define the largest amount of wind power production capacity that might disconnect due to the subsynchronous oscillation phenomena.

Looking at the scenarios for years 2027 and 2030, it can be seen that the differences between the amounts of wind power production capacity when using different Type-3 to Type-4 ratios are relatively large in most of the presented substations. In other words, there is significant amount of wind power production capacity from WPPs that have unknown wind turbine type, which can also be seen from Figure 5. This means that the amount of wind power production capacity from Type-3 wind turbines is sensitive to the used Type-3 to Type-4 ratio. As it can be seen from Figure 11, if any of the presented substations in scenarios 2027 or 2030 happens to have the Type-3 to Type-4 ratio of 1:0, or in other words all the new WPPs in any of the substations happen to have Type-

3 wind turbines, the amount of wind power production capacity from the Type-3 WPPs is around twice as much compared to when using the ratio of 1:2.

Let us look at the scenario 2027 and substations 11 and 8 as an example. If the actual Type-3 to Type-4 ratio that comes true is 1:2 in substation 11 and 2:1 in substation 8, it can be seen that the highest amount of wind power production capacity that could potentially disconnect in the scenario 2022 is defined by the substation 8, not by the substation 11. Similarly in scenario 2030, if substation number 11 has a ratio of 1:2 and substation number 8 has a ratio of 1:0, the highest amount of potentially disconnecting wind power production capacity is defined by the substation number 8 and not by the substation number 11. Therefore, it is not easy to estimate which substation will have the most potentially disconnecting wind power production capacity.

Next, let us analyse the results presented in Figure 12, that presents the amounts of estimated disconnecting wind power production capacity, calculated by using the assumption that only the WPPs with the Type-3 wind turbines and rated power of 60 MW or less will disconnect as a result of undamped subsynchronous oscillations.

As it can be seen from Figure 12, the differences between the amounts of wind power production capacity when using different Type-3 to Type-4 ratios are smaller in most of the presented substations compared to the difference in amounts presented in Figure 11. Thus, it can be concluded that considering the Type-3 WPPs with rated power of 60 MW or less, the wind turbine types of the WPPs are relatively more well-known compared to the WPPs with rated power greater than 60 MW, or a large part of the unknown WPPs have rated power over 60 MW. It can also be seen from Figure 12 that there is no great difference when using different Type-3 to Type-4 ratios in scenario 2022, compared to the scenarios 2027 and 2030. Thus, the wind turbine types of the WPPs with rated power of 60 MW or less are well known in scenario 2022.

There are however a few assumptions and simplifications made while calculating these preliminary results. The discussion on how realistic the amounts of potentially disconnecting wind power production capacity are in reality and what additional investigations might be required is conducted in Section 7.1

6.2 Immunity of the manufacturer Type-4 wind turbine

The sequence in the first part of the investigation described in Section 5.2.2 is performed to the manufacturer Type-4 WPP model in order to investigate the immunity of the manufacturer Type-4 WPP to the SSCI phenomena, however there is not a single configuration in the sequence where the Type-4 WPP is causing undamped or sustained subsynchronous oscillations. Thus, it can be concluded that the specific investigated manufacturer Type-4 WPP does not cause SSCI phenomenon by itself in the Finnish series compensated transmission network.

Next, the results from the second part of the investigation described in Section 5.2.2 are presented, where the generic Type-3 WPP output is observed when the parallel connected manufacturer Type-4 WPP is in service and out-of-service. The simulation model and the parameter values used are presented in Figure 8 and Table 4, respectively. In Figure 13 the output current of the generic Type-3 WPP in the point of common coupling (PCC) is shown in cases where a) the manufacturer Type-4 WPP is in service and b) out-of-service.

The additional damping was added on the generic Type-3 WPP connection line, in order to more clearly show the effect of the investigated manufacturer Type-4 WPP on the damping of subsynchronous oscillations. It should be noted that the results in Figure 13 are acquired using the less detailed Type-3 WPP model, due to the fact that the less detailed model is faster to configure so that the oscillations are just barely undamped.

As it can be clearly seen from Figure 13, when the Type-4 WPP is out-of-service the amplitude of the oscillations increases much more rapidly compared to the case where the Type-4 WPP is in service. Thus, it can be concluded that the investigated Type-4 WPP dampens the oscillations, at least in case where the oscillation frequency is roughly 25 Hz.

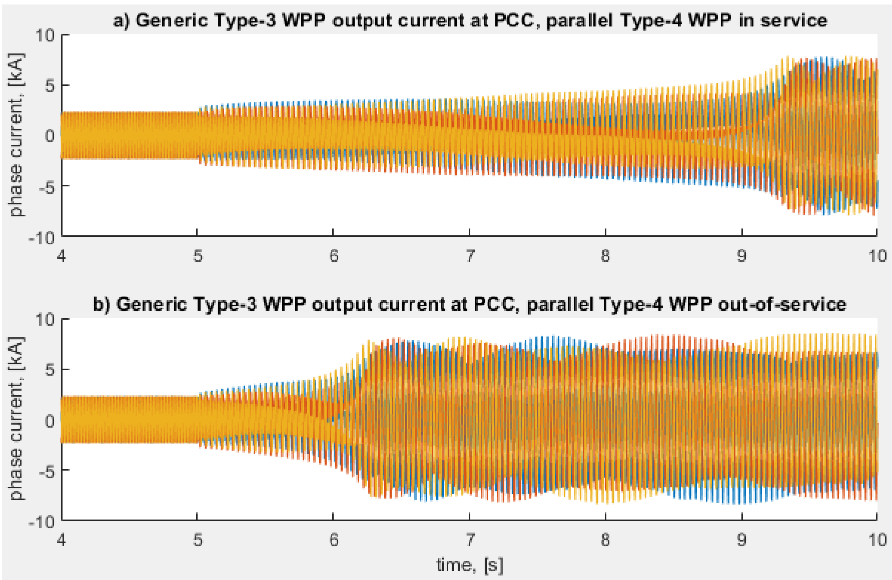

Figure 13: Output current of the generic Type-3 WPP, with parallel connected manufacturer Type-4 WPP is a) in service and b) out-of-service. Oscillation frequency is in both cases roughly 25 Hz. Results are from the second part of the investigation presented in Section 5.2.2. The simulation model is presented in Figure 8 and the parameters of the model are presented in Table 4.

Next, Figure 14 presents the results from the third part of the investigation described in Section 5.2.2, where the response of the Type-4 WPP was investigated when the parallel connected generic Type-3 WPP was causing undamped W-SSCI. The simulation model and the parameter values used are presented in Figure 8 and Table 5, respectively. The output currents of both WPPs and the PCC voltage are presented in a case where the detailed generic Type-3 WPP, connected in parallel with the investigated manufacturer Type-4 WPP model, is causing highly undamped W-SSCI. The case is the same as presented above, only the more detailed Type-3 WPP model is used and the additional damping in the Type-3 WPP connection line is removed. As it can be clearly seen from Figure 14, even when the PCC voltage oscillation is remarkably high, the current oscillation of the Type-4 WPP is nowhere near the level of current oscillation experienced by the generic Type-3 WPP. Thus, it can be concluded that the protections of Type-3 WPP should trip much faster than a Type-4 WPP connected to the same PCC.

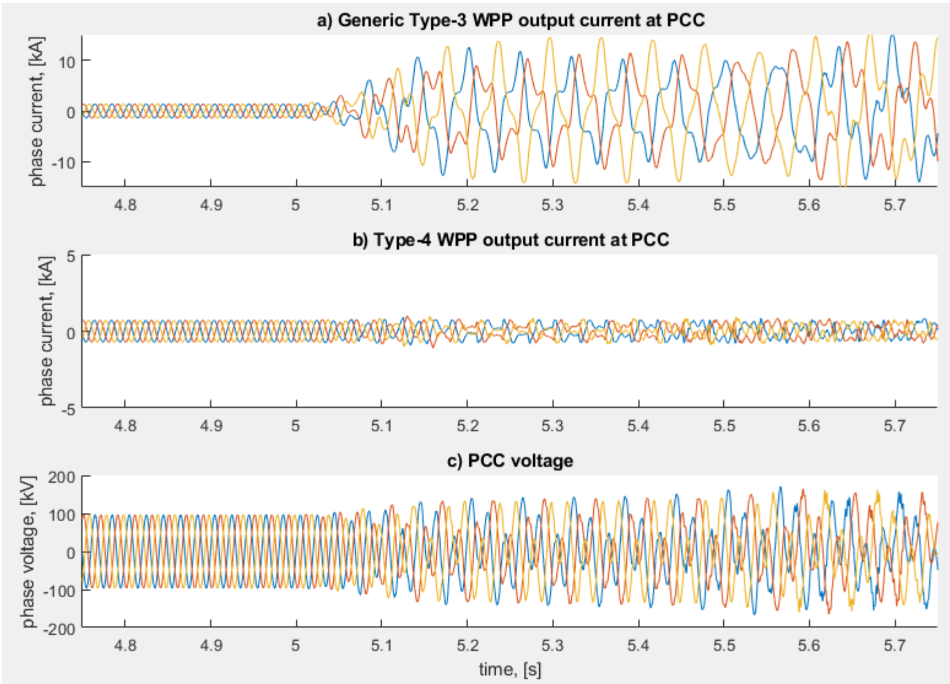

Figure 14: Output currents of the a) generic Type-3 WPP and b) manufacturer Type-4 WPP at the PCC, as well as c) the PCC voltage. Results are from the third part of the investigation presented in Section 5.2.2. The simulation model is presented in Figure 8 and the parameters of the model are presented in Table 5.

From the results above it can be concluded that the investigated manufacturer Type-4 WPP can be considered immune to the subsynchronous oscillations. This does not prove that all the Type-4 WPPs are immune to the phenomenon, and the immunity of different Type-4 WPPs should always be investigated separately. However, this case does provide some validation for the assumption that the Type-4 WPPs generally are immune to the subsynchronous oscillation phenomenon which is made in Chapter 4. This result is also in line with the literature and published real-world events.

6.3 Sensitivity of the generic Type-3 wind turbine

The sequence described in Section 5.2.3 is performed to the generic Type-3 WPP model. The simulation was performed in order to investigate how sensitive the generic Type-3 WPP model is to cause the undamped W-SSCI Contrary to results from the manufacturer Type-4 WPP, the generic Type-3 WPP causes undamped subsynchronous oscillations in every configuration of the sequence. Thus, it can be concluded that the generic Type-3 WPP model used in this thesis is sensitive to causing undamped W-SSCI phenomenon.

Although the observed susceptibility of the Type-3 WPP to cause undamped W-SSCI is in line with the literature, the sensitivity of the used generic Type-3 WPP model described above might be even a little too conservative for a generic model. The behaviour of the generic Type-3 WPP is discussed more in Section 7.3.

6.4 Need of the protection in the manufacturer Type-4 wind turbine

In this section the findings from the study with the manufacturer Type-4 WPP model are presented. The need of specific subsynchronous oscillation protections in certain manufacturer Type-4 wind turbine model connected to Finnish series compensated transmission network was investigated using the method developed in Section 5.3.1.

The first step of the study was to validate that the manufacturer Type-4 WPP does not cause or amplify any subsynchronous oscillations when connected to series compensated network. The investigated manufacturer Type-4 WPP was found immune to the subsynchronous oscillations based on simulation results presented in Section 6.2

The Type-4 WPP might still be susceptible to undamped subsynchronous oscillations caused by any other nearby WPPs, therefore the next step was to define a worst-case scenario using parallel connected generic Type-3 WPP. The worst-case scenario was identified based on the highest phase voltage instantaneous peak value in the PCC. The identified cases with the highest observed voltage are presented in Figure 15 with the transformer saturation disabled and enabled. The worst-case scenarios for both cases with transformer saturation enabled and disabled were found with the sequence parameters presented in Table 8.

Table 8: The parameter values that caused the worst-case, i.e. the highest voltage oscillations in the PCC, when parameter values of the Table 7 were varied in the simulation model presented in Figure 10.

Parameter	Varied values
Type-3 WPP rated output	200 MW
Series compensation level (and corresponding MOV protective voltage level)	85 % (286 kV)
400 kV network equivalent strength	12000 MVA

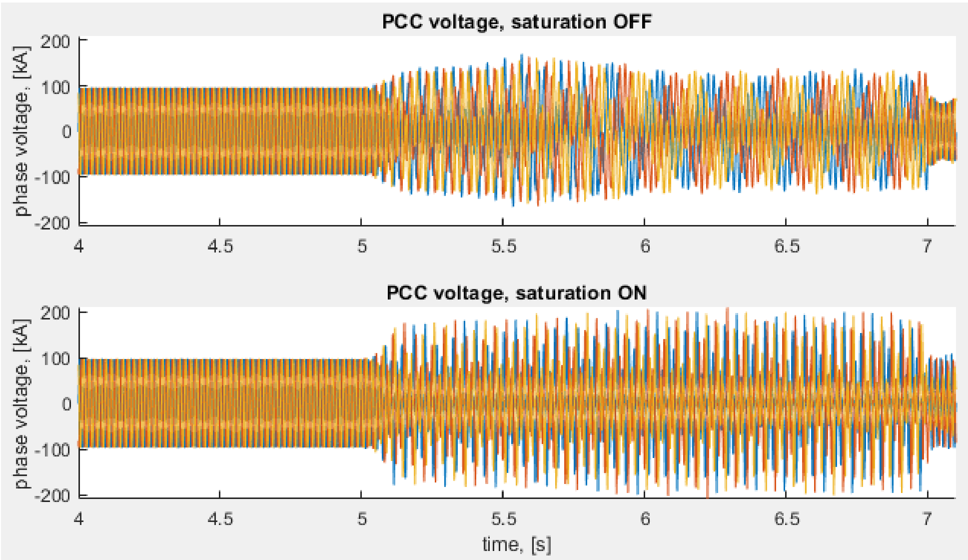

Figure 15: PCC voltage with transformer saturation disabled and enabled, during the worst-case voltage oscillations in the PCC. The worst-case parameter values are presented in the Table 8, for the simulation model presented in Figure 10.

As it can be seen from Figure 15, with the transformers' saturation enabled the PCC voltage is significantly greater compared to when the transformer saturation is disabled. Therefore, when defining the worst-case scenario, the transformer saturation should be enabled in each transformer included in the simulation. Thus, all the following results discussed have the transformer saturation enabled.

From the worst-case scenario presented above, it can be determined that in the 110 kV bus of the substation (PCC) the highest phase voltage instantaneous peak value is around 200 kV (around 2 pu, the base phase voltage peak value is 96.3 kV). This voltage should be endured by the investigated Type-4 WPP, if no specific subsynchronous oscillation protections are implemented in the investigated Type-4 WPP. The frequency of the oscillations in the worst-case presented above was around 22 Hz.

Figure 16 shows the output currents of both WPPs in the 110 kV PCC level (high voltage side of the connecting transformer). The need of the protections should be however investigated by looking at the turbine level currents.

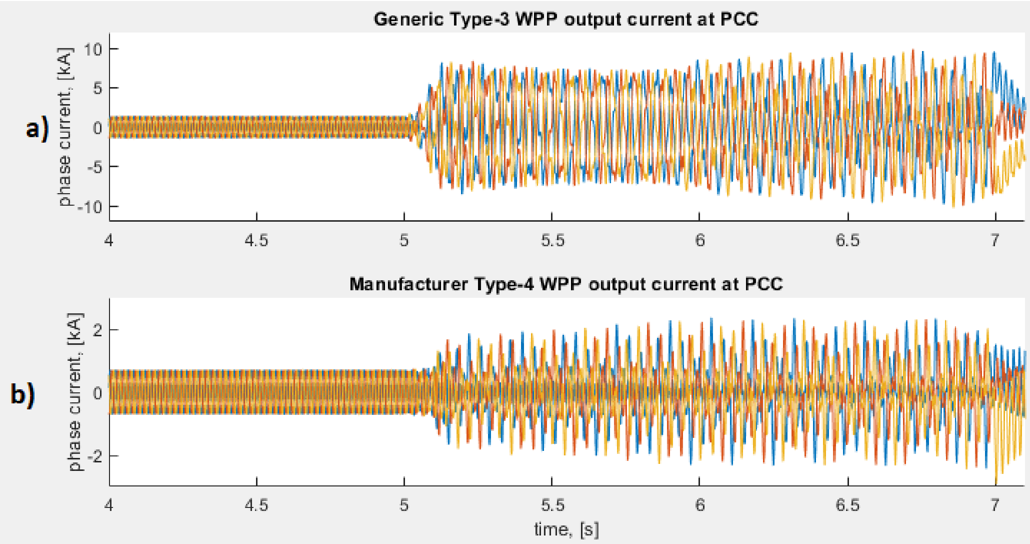

Figure 16: The output currents of a) generic Type-3 WPP model and b) manufacturer Type-4 WPP model at PCC, during the worst-case voltage oscillations in the PCC. The worst-case parameter values are presented in the Table 8, for the simulation model presented in Figure 10.

In Figure 17 the current and the voltage in the Type-4 wind turbine terminal (low voltage side of the aggregated wind turbine transformer) are presented in the worst-case scenario. It should be noted that the measurements are from the terminal of aggregated turbine model which includes multiple Type-4 wind turbines. The figure shows that even during the highest estimated subsynchronous voltage oscillations in the PCC caused by the nearby Type-3 WPP, the magnitude of the Type-4 wind turbine output current and voltage stay in relatively low values. It should be noted that the behaviour of the wind turbine output current is notably different in the 110 kV PCC level compared to the low voltage wind turbine terminal level. This is due to the saturation of the transformers that occurs because of to the high amplitude subsynchronous current oscillations.

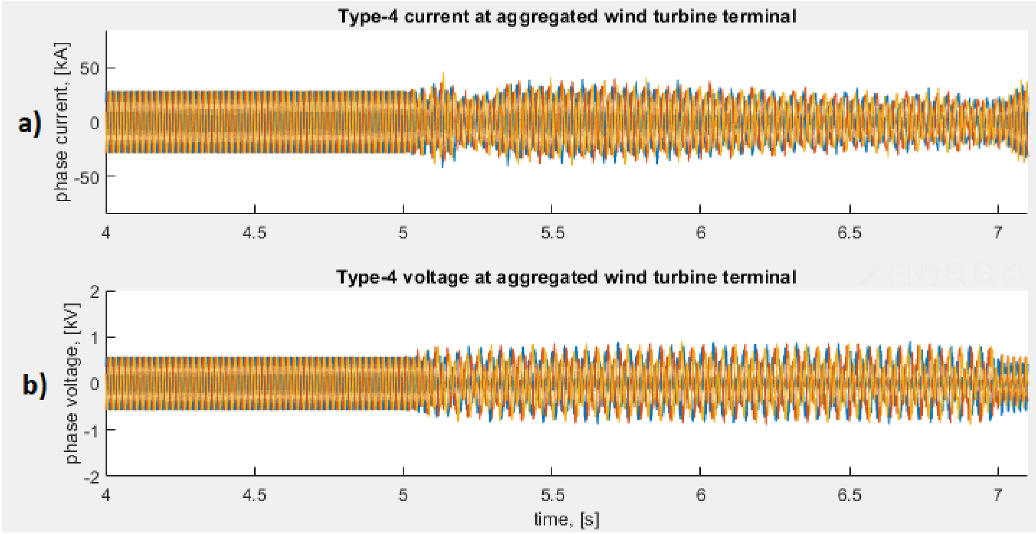

Figure 17: Type-4 aggregated wind turbine terminal a) current and b) voltage during the worst-case voltage oscillations in the PCC. The worst-case parameter values are presented in the Table 8, for the simulation model presented in Figure 10.

The tolerance to high amplitude subsynchronous current and voltages could be unique for different wind turbines, and thus the resiliency of the wind turbines should be always confirmed with the manufacturer. After presenting the above results from the study to the Type-4 wind turbine manufacturer, they confirmed that the worst-case scenario does not create a risk for damages in the investigated Type-4 wind turbines. Therefore, the investigated Type-4 wind turbine is not required to have a specific subsynchronous oscillation protection implemented.

6.5 Functionality of the protection in the Type-3 wind turbines

In this section the desired functionality of the subsynchronous oscillation protections in the Type-3 wind turbines are presented. The method for validating the functionality of the protection is presented in Section 5.3.2.

The subsynchronous oscillation protection of the Type-3 wind turbine should operate according to the magnitude and duration of the subsynchronous oscillation. The operation time of the protection should be faster when the magnitude of the subsynchronous oscillations is higher, and vice versa. The reason for this is that the wind turbines that are causing the interaction the most would also most likely trip first. This could be achieved for example with an inverse time protection. Tripping only the necessary part of the wind turbines is essential since tripping only part of the wind turbines in the WPP might reduce the negative resistance enough and dampen the subsynchronous oscillations, and some of the wind turbines could continue operation. Therefore, the protections should be implemented in each wind turbine, as already required in the protection requirements [8].

However, due to the complicated nature of the oscillation phenomenon, it is difficult to devise general and precise requirements for the subsynchronous oscillation protection in all Type-3 wind turbines. Also, formulating the precise requirements was not an objective in this thesis. Therefore, the desired operation time of the protection in different magnitudes of oscillation is for now defined broadly and using engineering judgement.

Figure 18 a) presents the output current of the Type-3 WPP in a case where the output current contains high amplitude subsynchronous component, and the WPP could be the major cause for the oscillations. In situations like these the subsynchronous oscillation protection of the Type-3 wind turbine should operate as fast as possible. However, Fingrid's fault ride through (FRT) requirements [45] should also be fulfilled and thus the proposed maximum operation time could be for example around 1 second from the beginning of the oscillations.

Figure 18 b) presents the output current of the Type-3 WPP in a case where the Type-3 wind turbines contributes much less to the oscillations, and it is possible that the major cause of the undamped oscillation is another nearby WPP. In situations like these the subsynchronous oscillation protection of the Type-3 wind turbines should operate more slowly, giving time for any other WPP or wind turbine that might be more prominent in causing the oscillations to trip first. Therefore, the proposed operation time could be for example somewhere between 1.5 – 2.0 second.

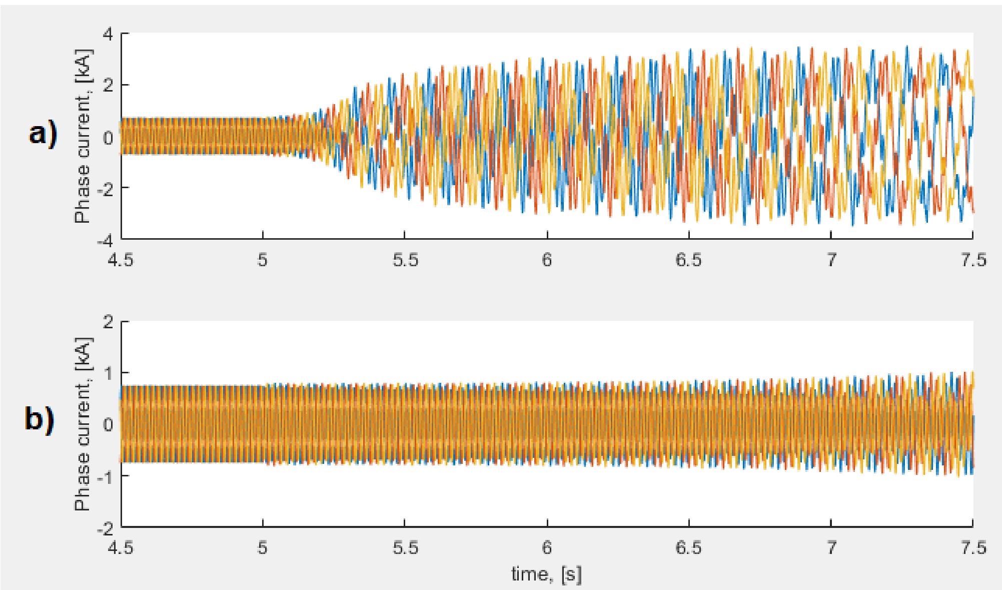

Figure 18: Two example waveforms for the Type-3 WPP output current in scenarios where the subsynchronous oscillation protection trip should be a) fast and b) slower

In cases where the subsynchronous oscillations are low amplitude and sustained, the wind turbine might have to be disconnected due to power quality issues the WPP is causing in the connection point, even though the low magnitude oscillations do not pose a risk for wind turbines or series capacitors. Defining how the protection should operate in these cases is however outside the scope of this thesis.

Let us assume that the graphs presented in Figure 18 a) and Figure 18 b) are outputs of different wind turbines in different nearby WPPs. These cases are most likely easy to differentiate using a method presented in Section 5.3.2, and thus the wind turbines that are causing the undamped oscillations the most (Figure 18 a) are likely to be correctly disconnected. In other words, the protection is selective in the aforementioned case. However, when there is less difference in the response between the Type-3 wind turbines, the selectivity of the protection cannot be fully guaranteed. Selectivity of the protection means in this case that only the necessary amount of wind turbines is disconnected in order to stop the undamped subsynchronous oscillations. Therefore, the second step of the protection validation method presented in Section 5.2.3 is required.

7. DISCUSSION AND FUTURE RESEARCH

In this chapter, the results presented in Chapter 6 are discussed. The possible assumptions and simplifications, as well as the effects of these on the results are discussed. Suggested concrete actions and future research topics are also presented.

7.1 Disconnecting amount of wind power production capacity

As presented in Section 6.1.1 the maximum amount of potentially disconnecting wind power production capacity due to the subsynchronous oscillation phenomena is significant in the 2027 and 2030 scenario, especially with the conservative assumption that all the Type-3 wind power production capacity in a single substation will disconnect.

The largest stepwise power change that the Finnish power system can withstand in the connection point of a power plant without compromising system security is 1300 MW [42, p. 6]. Since the amount of potential disconnecting wind power production capacity may be higher than 1300 MW in the scenario 2030, and almost as much in scenario 2027, it can be concluded that subsynchronous oscillations may create a system level risk.

It is however unlikely that the whole amount of potentially disconnecting wind power production capacity is disconnected at the same time. The subsynchronous oscillation protections are to be implemented in each Type-3 wind turbine. If selective protections are implemented in the wind turbines, part of the wind turbines are first disconnected and the negative damping created by the Type-3 WPPs could reduce to a level where the oscillations dampen, without needing to disconnect all the wind turbines in the Type-3 WPPs.

In the investigation it is assumed that all the WPPs that are disconnected due to the subsynchronous oscillations are operating at the rated power. This will probably not occur often, since the WPPs output power depends highly on the wind conditions that can change constantly.

Also, as discussed in Sections 2.4.4, the risk for subsynchronous oscillation phenomena in the Type-3 wind turbines is greater when the output power of the turbine is lower. The amount of disconnecting wind power is thus most likely far less than the rated output power (i.e. the production capacity) of the WPPs.

In Section 5.2.1 the ratio of 1:0 was chosen to represent the worst-case where all the new WPPs in the substation happen to be Type-3 WPPs. However, it can be considered unlikely especially in the substations with large amount of wind power production capacity, considering that the current Type-3 to Type-4 ratio in the whole system is currently 1:2. In the investigation a conservative assumption is also made that the minimum amount of wind power production capacity from Type-3 WPPs is defined by the ratio of 1:2, although it is similarly plausible that all the new WPPs are Type-4 WPPs.

Unfortunately, knowing well beforehand if a decided WPP will have Type-3 or Type-4 wind turbines can be difficult, due to how fast the wind turbines can be installed after the permission is granted. This can be seen from Figure 5, which shows that when writing this thesis (in 2021) there are still WPPs with unknown wind turbine type in the 2022 scenario. As the type of the wind turbines majorly determines the possibility of subsynchronous oscillations in the connection point, the wind turbine types of the planned WPPs should be inquired well ahead of time in order to investigate the risk of subsynchronous oscillations more precisely.

If the more reasonable assumption, where only the Type-3 WPPs with rated power of 60 MW or less will disconnect as a result of subsynchronous oscillation phenomena, is considered, the maximum amount of disconnecting wind power production capacity is relatively small, especially if the points discussed above are considered. Since the WPPs with rated power of 60 MW or less are not required to connect directly to the substation, those WPPs could be connected along the 110 kV lines. This increases the distance to the series capacitors and thus provides additional damping, which could be enough to nullify the possible high negative resistance in case of some of the WPPs. Therefore, changing the damping requirement to also involve the WPPs with rated power of 60 MW or less is not seen necessary for now. If the amount of WPPs with rated power of 60 MW or less significantly changes in the future, the changing the rated power limit of the damping requirement could be considered.

As mentioned in Chapter 4, the Fingrid’s damping requirements [8] only mention that the damping of the WPPs with rated power over 60 MW has to be sufficient in the connection point, meaning that the damping is not necessarily required to be positive. However, in order to treat all connecting WPPs equally, the required level of damping is in this thesis recommended to be positive for all investigated WPPs with rated power over 60 MW. If negative damping that is considered sufficient is allowed for certain WPPs, the other WPPs that are connecting to the same connection point in the future might have to provide relatively more damping to compensate for the negative damping of the existing WPPs.

In the investigations only the potential amount of disconnecting wind power production capacity is investigated, which can be though to represent the magnitude of the subsynchronous oscillation risk in each substation. The likelihood of the appearance of undamped subsynchronous phenomena should also be investigated in order to better understand how great the risk in different substations is in reality. As explained in Section 2.4.1, the network configurations where the Type-3 WPP is left connected to the rest of the network only through series compensated lines can be considered as the most dangerous conditions regarding the W-SSCI phenomenon, however the risk could also exist in other configurations. At least in the Finnish highly meshed series compensated transmission system, the risk of W-SSCI is not always easily deducible only by looking at the topology of the network in the WPP connection point [24]. The likelihood should be investigated for example by calculating the damping of the network side in the WPP connection point in numerous different network configurations using the frequency scanning methods. However, this investigation also requires studies on what level of damping could be considered to present the possibility for the undamped subsynchronous oscillations.

In Section 5.2.1 it is also assumed that the possible subsynchronous oscillation phenomena are limited to only single substation. It is assumed that the 400 kV transmission lines between the substations provide enough damping for the subsynchronous oscillations, thus preventing high magnitude voltage oscillations from spreading into the 110 kV busses of the nearby substations. This assumption should however be validated in the near future. However, as mentioned in Section 5.2.1, the assumption that the risk of oscillations does not appear in multiple substations at the same time cannot be validated with the data presented in Chapter 4, and should also be investigated thoroughly in the future.

All in all, the results presented in Section 6.1.1 attempt to present the preliminary and conservative estimation of the maximum amount of wind power production capacity that could potentially be disconnected due to the subsynchronous oscillation phenomena. The results show that there will be significant amount of wind power production capacity that could potentially disconnect in certain substations that could even pose a system level risk in the Finnish transmission system. Thus, the damping and the protection of subsynchronous oscillations in the WPPs located especially in the presented substations should be investigated thoroughly. Fortunately, due to the assumptions discussed above the amount of disconnecting wind power production capacity, and wind power production, is likely not as great as it is presented to be in the results, however the investigations described in this section are required in order to acquire more accurate estimations.

7.2 Immunity of the Type-4 wind turbines

As presented in Section 6.2, the investigated manufacturer Type-4 WPP can be considered immune to the SSCI phenomenon in the Finnish series compensated network, and it also behaves passively when exposed to undamped subsynchronous oscillations caused by any other nearby WPPs. Although this does not prove that all the Type-4 WPPs are immune to the SSCI phenomenon, this case does provide some validation for the assumption that the Type-4 WPPs generally are immune to the subsynchronous oscillation phenomenon.

However, the investigations are performed on a benchmark model, where the Type-4 WPP model might not have all the parameters of the wind turbine controls similarly as in real-world WPP. Thus, in theory there could still be a risk for subsynchronous oscillations in the real-world implementations, although the likelihood of this should still be low. Therefore, it cannot be guaranteed that the investigated Type-4 wind turbines are immune to the SSCI phenomenon in real-world implementations. In theory, the investigations would have to be performed for each individual WPP and with the real network model, in order to better ensure the immunity of the WPP. This could however lead to a large workload. Despite the case specific investigations performed with current knowledge, due to the complicated nature of the phenomenon the possibility of the WPP causing subsynchronous oscillations might still exist, and thus the immunity still cannot be completely guaranteed.

The immunity and the passivity of the manufacturer Type-4 WPP is investigated in this thesis only with time domain simulations using the sequences described in Section 5.2.2, due to the lack of available proper dynamic impedance scanning tool. With the impedance scanning tool, the susceptibility of the WPP to undamped subsynchronous oscillations could be investigated much better. The effective impedance of the WPP could be determined for the whole subsynchronous frequency range in single WPP operation point. This would provide significant time savings compared to only performing the time domain simulations, and thus allow for a faster extensive study. The time domain analysis performed in this thesis would only be required to validate the results. Although these dynamic impedance scans are acquired from the WPP manufacturer due to the requirements described in Chapter 4, the scanning could also be used to determine the effective impedance of a larger system with multiple WPPs and other non-linear devices, such as FACTS and HVDC systems. Thus, it is highly recommended to invest in a proper dynamic impedance scanning tool.

In this thesis, the generic Type-4 WPP model was available but not used in any of the simulations. There might be however need for the generic model in the future studies, which is why the investigations performed here for the manufacturer Type-4 WPP model should also be performed for a generic Type-4 WPP model. In addition, the results from the real-world model presented in this thesis could be used to compare and validate the generic Type-4 WPP model.

7.3 Sensitivity of the Type-3 wind turbines

As mentioned in Section 6.3, the investigated generic Type-3 WPP model caused undamped subsynchronous oscillations in every configuration of the study sequence.

The generic Type-3 WPP can therefore be considered extremely sensitive to causing undamped W-SSCI in the series compensated system. A manufacturer Type-3 WPP model is not investigated in the thesis, however according to preliminary studies made on certain manufacturer Type-3 WPP model alongside the other investigations, the difference to the generic Type-3 WPP model could be seen clearly. The studied manufacturer Type-3 WPP model was significantly less sensitive to causing undamped W-SSCI, and the magnitude of the observed subsynchronous current component was not as high during the undamped W-SSCI event, compared to the generic Type-3 WPP.

Therefore, the generic model used in this thesis is not recommended to be used in simulations that study the likelihood of the W-SSCI for example in different network topologies, contingencies or outages. The model could however be used in studies that investigate for example the behaviour of other WPPs during an undamped subsynchronous oscillation phenomenon, as is done in the simulations of this thesis. The magnitude of the oscillations created by the generic Type-3 WPP is conservative due to lack of specific subsynchronous oscillation damping capabilities and components restricting the current.

Investing in a PSCAD model of a generic Type-3 WPP that more accurately models the behaviour of real-world Type-3 WPPs is recommended. The more accurate model could be used to investigate the realistic likelihood of subsynchronous oscillations in different topologies of contingencies.

7.4 Type-4 wind turbine subsynchronous oscillation protections

The subsynchronous oscillation protections are not required in the investigated Type-4 wind turbines, due to the investigated Type-4 WPPs immunity to the subsynchronous oscillations and ability to withstand the worst-case scenario created with the parallel connected generic Type-3 WPP, presented in Section 6.4.

However, part of the reason why the protections are not required is due to the observed immunity and passivity of the investigated Type-4 wind turbines. As mentioned in Section 7.2 the immunity cannot be completely guaranteed, although the risk of undamped subsynchronous oscillations can be considered low. Therefore, although the protections are not mandatory in the investigated Type-4 wind turbines, the risk can still exist and ultimately the decision is made by the WPP owner.

There are however other components in the real-world Type-4 WPPs aside from the wind turbine itself that can also be exposed to the subsynchronous currents and voltages. Therefore, the stresses seen in different parts of the WPP network should be investigated by the WPP owner. If the WPP components in the medium or high voltage level do not withstand the worst-case scenario, the subsynchronous oscillation protections should be implemented in the WPP. The placement of the protections will depend on the vulnerable components. The studies should be made specifically for each project to determine the sufficient withstand for all WPP components. The estimation of worst-case subsynchronous voltage oscillations visible in the PCC could be provided to the WPP owner by Fingrid.

7.5 Type-3 wind turbine subsynchronous oscillation protections

As presented in Section 6.5, the operation of the Type-3 wind turbine subsynchronous oscillation protection should desirably operate depending on the magnitude of the undamped oscillations, in order to first disconnect the wind turbines that are majorly causing the oscillations. Also, a rough description of what parameters should be varied and what investigations are required in order to validate this functionality are presented in Section 6.5.

As mentioned in Section 3.2.3, bypassing the series capacitor in order to stop the undamped subsynchronous oscillations is not always the most optimal solution. Thus, the subsynchronous oscillation protection in the series capacitor should only operate as a backup, and primarily to protect the series capacitor from damages. Thus, the wind turbines' subsynchronous oscillation protection should ideally be tuned so that it operates before the series capacitors protection.

Many of the WPPs are connected to the 110 kV bus of the 400/110 kV substation, meaning that the low magnitude and sustained subsynchronous oscillations possibly caused by the wind turbines can create power quality issues for others connected to the same substation. In the Finnish transmission system, there can be other customers, for example loads and other generation, connected to the same 110 kV bus with the WPPs. Although these low magnitude oscillations might not pose a risk for damages in the WPPs or in the series capacitor, the WPPs might still be required to disconnect in case where the power quality of the PCC is impaired.

The desired functionality of the subsynchronous oscillation protection is roughly devised and demonstrated in Sections 5.3.2 and 6.5, respectively. The functionality is presented roughly, due to the fact that the precise functionality of the protection is not described in the subsynchronous oscillation protection requirements, and devising these requirements was not an objective of this thesis. It is also mentioned in 6.5 that the selectivity of the protection cannot be totally guaranteed by only validating the roughly devised functionality.

Considering the discussion above, it is recommended that the studies on subsynchronous oscillation protections are continued in the future. The requirements of the protections should be more precise on how the protections should be implemented, confirm the selectivity of the protections, consider the coordination with the series capacitor protection, and finally manage the possible power quality issues.

8. CONCLUSIONS

This thesis investigates the maximum amount of potentially disconnecting wind power production capacity due to the undamped subsynchronous oscillations caused by the interaction between wind power plants and series compensated network and develops methods for validating the need and functionality of the subsynchronous oscillation protections of Type-4 and Type-3 wind turbines, respectively.

Based on the literature and the investigated real-world subsynchronous oscillation events, the wind power plants with Type-3 wind turbines are identified to have a significant risk of causing undamped subsynchronous oscillations and disconnecting from the network due to the oscillations. The wind power plants with Type-4 wind turbines however are perceived to be immune to subsynchronous oscillation phenomena in a series compensated network according to most of the literature, investigated real-world subsynchronous oscillation events, and simulations performed in this thesis using a single manufacturer Type-4 wind power plant model. In the thesis it is acknowledged that the immunity of Type-4 wind turbines should not be assumed, and the immunity of different Type-4 wind turbines should be investigated separately.

In the thesis the maximum amount of potentially disconnecting wind power production capacity due to the undamped subsynchronous oscillations is investigated in a set of substations that are in the vicinity of the series capacitors and have wind power plants connected to them in the future scenarios. The maximum amount of potentially disconnecting wind power production capacity is determined in each substation by the maximum amount of production capacity from wind power plants with Type-3 wind turbines. The substations with the largest amount of potentially disconnecting amount of wind power production capacity were also identified in each future scenario.

The conservative estimations show that the highest amount of disconnecting wind power production capacity could be in range of 340–775 MW in 2022, 520–1225 MW in 2027, and 850–2225 MW in 2030. Fortunately, the probable amount of disconnecting wind power production is likely not as great as the maximum amounts of disconnecting wind power production capacities presented above, for example due to the risk of undamped subsynchronous oscillation being higher when the output power of the Type-3 wind turbine is lower. However, in future it should still be investigated if the risk of subsynchronous oscillations can appear on multiple substations at the same time.

The risk of subsynchronous oscillations can be considered greater in Type-3 wind power plants that have rated power of 60 MW or less, due to the lack of subsynchronous oscillation damping requirements on these wind power plants. Fortunately, the amount of production capacity from Type-3 wind power plants with rated power of 60 MW or less is relatively small in the future scenarios, compared to the total amount of wind power production from all Type-3 wind power plants. The WPPs with rated power less that 60 MW also have the possibility to connect along the 110 kV transmission lines, that can provide enough damping to nullify the negative damping of the WPP.

The method for validating the need of specific subsynchronous oscillation protection in Type-4 wind turbines connected to series compensated network is developed in the thesis using a single manufacturer Type-4 WPP model. The proposed method includes 1) the validation of the immunity to subsynchronous oscillations, 2) defining the worst-case scenario using parallel connected generic Type-3 wind power plant, and 3) discussions with the wind turbine manufacturer.

It is proposed that if the investigated Type-4 wind turbine does not cause undamped subsynchronous oscillations by itself and can withstand the worst-case subsynchronous oscillations caused by another nearby wind power plant, the specific subsynchronous oscillation protections should not be mandatory for the investigated wind turbine. In the thesis the method was performed on a single manufacturer Type-4 WPP model, which resulted in the investigated Type-4 wind turbines not required to have specific subsynchronous oscillation protection.

Because the risk of subsynchronous oscillation phenomena in Type-3 wind turbines is identified to be significant, the subsynchronous oscillation protections should be mandatory for all Type-3 wind turbines. As the functionality of the protections are not precisely defined in the subsynchronous oscillation protection requirements set to wind turbines by Fingrid, the desired functionality was roughly devised and proposed.

The validation of the Type-3 wind turbine subsynchronous oscillation protection functionalities can be performed for example by injecting subsynchronous voltage or current of certain frequency on top of the fundamental voltage or current in the wind turbine terminal, and by varying the magnitude and frequency of the injected current or voltage. The selectivity of the protection should be further investigated using another parallel connected Type-3 wind power plant in order to validate that the wind turbines that are most significantly causing the oscillations are disconnected first.

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APPENDIX A:

Table A: Wind power production capacity from Type-3, Type-4 and unknown type WPPs estimated to be connected to each investigated substation. The capacity from WPPs with rated power of 60 MW or less is also separately presented.

	TYPE-3 TOTAL PRODUCTION, MW			TYPE-3 < 60 MW, MW			TYPE-4 TOTAL PRODUCTION, MW			TYPE-4 < 60MW, MW			UNKNOWN TOTAL, MW			UNKNOWN < 60MW, MW		
	2022	2027	2030	2022	2027	2030	2022	2027	2030	2022	2027	2030	2022	2027	2030	2022	2027	2030
1	0	0	0	0	0	0	0	0	0	0	0	0	25	50	50	25	50	50
2	0	0	0	0	0	0	0	0	0	0	0	0	0	25	200	0	25	25
3	25	25	25	25	25	25	50	50	50	50	50	50	0	250	250	0	0	0
4	0	0	0	0	0	0	25	25	25	25	25	25	0	125	125	0	25	25
5	0	0	0	0	0	0	0	0	0	0	0	0	250	375	450	0	50	125
6	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	0	50	50
7	50	50	50	50	50	50	200	200	200	150	150	150	0	200	850	0	125	200
8	125	125	125	125	125	125	275	275	275	125	125	125	650	850	900	50	100	125
9	50	50	50	50	50	50	50	50	50	50	50	50	100	300	625	0	50	150
10	75	75	75	75	75	75	275	275	275	75	75	75	175	450	775	0	25	25
11	175	175	175	175	175	175	0	0	0	0	0	0	75	1050	2050	75	275	275
12	125	75	75	0	0	0	225	100	100	50	25	25	50	50	75	50	50	75
13	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	0	25	50
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	150	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	300	0	0	0
16	0	0	0	0	0	0	200	300	300	100	100	100	50	300	325	50	225	250
17	25	25	25	25	25	25	0	0	0	0	0	0	75	125	525	75	125	150
18	0	0	0	0	0	0	150	150	150	150	150	150	0	550	650	0	75	75
19	0	0	0	0	0	0	0	0	0	0	0	0	0	50	150	0	50	150
20	75	75	75	0	0	0	275	275	275	50	50	50	100	325	350	25	100	150
21		0	0		0	0		50	50		50	50		25	450		25	25
22		75	75		0	0		100	100		25	25		50	75		50	75
23		0	0		0	0		300	300		150	150		250	325		0	0
24			100			100			200			200			575			225
25			0			0			100			100			325			125
sum	725	750	850	525	525	625	1725	2150	2450	825	1025	1325	1550	5475	10650	350	1500	2400

APPENDIX B

Table B: Subsynchronous oscillation benchmark model, presented in Figure 7, components' constant values

Component	**Parameter**	Value
400 kV transmission line (single line)	Positive sequence resistance Positive sequence inductive reactance Positive sequency capacitive reactance	0,018 Ω/km 0,3 Ω/km 0,3 MΩ*km
110 kV transmission lines (single line)	Positive sequence resistance Positive sequence inductive reactance Positive sequency capacitive reactance	0,05 Ω/km 0,3 Ω/km 0,25 MΩ*km
400 kV / 110 kV / 21 kV transformer	Apparent power rating Windings #1, #2, #3 line to line voltage Windings #1, #2, #3 Positive sequence leakage reactance (#1-#2) Positive sequence leakage reactance (#1-#3) Positive sequence leakage reactance (#2-#3) Eddy current losses Copper losses (#1-#2) Copper losses (#1-#3) Copper losses (#2-#3) Air core reactance Magnetizing current Knee voltage	400 MVA 410 kV, 120 kV, 21 kV Y, Y, Delta 0,2053 pu 0,4377 pu 0,7545 pu 0,000253 pu 0,0020282 pu 0,0069992 pu 0,0090274 pu 0,4106 pu 0,03 % 1,19 pu
110 kV / 33 kV transformer, Only the values of the 110/33kV transformer connecting the aggregated generic Type-3 WPP are presented	Apparent power rating Windings #1, #2 line to line voltage Windings #1, #2 Positive sequence leakage reactance (#1-#2) Eddy current losses Copper losses Air core reactance Magnetizing current Knee voltage	varied 118 kV, 33 kV Y, Y 0,1 pu 0,0001 pu 0,0001 pu 0,2 pu 2,00 % 1,17 pu

APPENDIX C

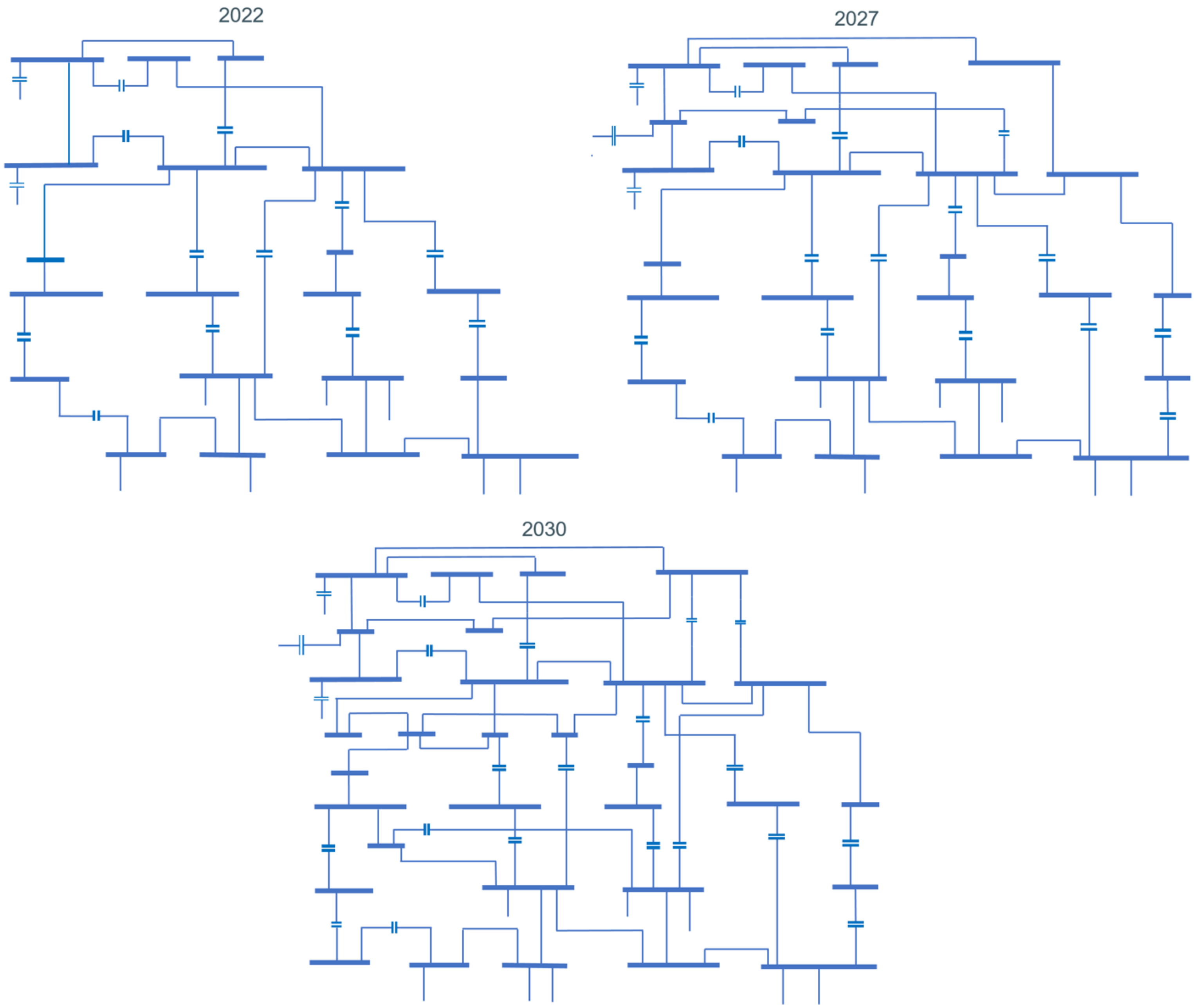

Figure C: Representation of the series compensated part of the 400 kV Finnish transmission system, in scenarios 2022, 2027 and 2030