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Study on the Reactive Power Behaviour of the Variable Frequency Transformer

Maren Skrunes

Master of Energy and Environmental Engineering
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Supervisor: Olimpo Anaya-Lara, IEL
Co-supervisor: Raymundo E. Torres-Olguin, Sintef

Norwegian University of Science and Technology
Department of Electric Power Engineering

Problem Formulation

The Variable Frequency Transformer (VFT) is proposed as a novel solution for interconnection of asynchronous electrical AC power systems. The VFT is a wound-rotor doubly fed induction machine used to control the flow of active power between two asynchronous power networks. The core technology of the VFT is a rotary transformer with three-phase windings on both rotor and stator. One power grid is connected to the rotor side of the VFT and another power grid is connected to the stator side. By regulating the torque applied to the rotor, through a motor drive system, the active power transfer through the VFT is controlled. The VFT is based on the principle of induction and thereby consumes reactive power. Depending on the operational conditions of the VFT, excessive reactive power will flow through the machine.

The VFT facilitates active power exchange between the two connected networks and it also provides a path for reactive power flows which are not fully controllable. The reactive power flowing through the VFT is determined by the needs of the two power systems coupled by the machine, thus the limitations to control reactive power flows is the reason why the VFT is unable to provide perfect isolation between the connected grids. Excessive amounts of reactive power may have a negative impact on power quality and system stability. The reactive power issue of the VFT is not elaborated in current literature, and there seems to be lack of research on the topic. Hence, the value and contribution of this research is the provision of understanding and bridging the gap in this area of knowledge. Key objectives are:

1. To provide an understanding of the fundamentals and basic operation of a VFT.
2. To investigate the reactive power requirements and characteristics of the VFT.

Abstract

The majority of the power system networks in the world today operate at a nominal frequency of either 50 or 60 Hz. Merging of adjacent power networks will expand the world's power supply system and thereby increase the possibility to utilize available power sources and deliver quality power. This Master's thesis investigates the Variable Frequency Transformer (VFT) concept, which has been proposed by General Electric as a solution for interconnecting two asynchronous networks whilst enabling controllable, bi-directional power flow between them. The mechanical design of the VFT is based on the well-known technologies of the hydro generator and the transformer. The core of the VFT is a rotary transformer, and it operates like a phase shifting transformer by adjusting the phase angle to transfer power between the two electrical networks. The principle of operation and fundamentals of the VFT are investigated with particular emphasis on understanding reactive power characteristics and requirements.

The VFT facilitates active power exchange between the two asynchronous networks and also provides a path for reactive power exchange which, however, is not fully controllable. A basic model of a 100 MW VFT interconnecting the two power networks is implemented in MATLAB/Simulink. A thorough study is conducted to understand the reactive power requirements for different operating conditions in terms of the power flow exchange between the two networks. Simulation results indicates substantial amounts of reactive power requirements in the machine during active power exchange. Two solutions are investigated to provide reactive power compensation, namely electromechanical capacitor bank and power electronic based STATCOM. Reactive power compensation by means of passive capacitor banks was able to improve system capacity and bring grid voltage to its nominal value. An active compensation by a STATCOM was investigated and a voltage regulation control scheme was suggested for implementing the STATCOM and the VFT in a combined system.

Sammendrag

De fleste elektriske kraftsystemer i verden i dag opererer med en nominell frekvens på enten 50 eller 60 Hz. En sammenkobling av nærliggende kraftsystemer vil utvide verdens totale strømforsyningssytem og dermed øke muligheten til å utnytte tilgjengelige energikilder og levere energi av høy kvalitet. Denne masteroppgaven skal undersøke konseptet rundt en Variabel Frekvens Transformator (VFT), foreslått av General Electric for sammenkobling av asynkrone nett. En VFT muliggjør en kontrollert, toveis effektoverføring mellom de asynkrone systemene. Den mekaniske utformingen til maskinen er basert på de velkjente teknologiene bak hydrogeneratoren og transformatoren. Maskinens kjerne er en roterende transformator som fungerer som en faseskifts transformator ved å justere fasevinkelen for å overføre kraft mellom de to elektriske nettene. De grunnleggende prinsippene og funksjonen til en VFT skal undersøkes, med særlig vekt på å forstå egenskapene og oppførselen til den reaktive effektflyten i maskinen.

En VFT gjør det mulig å overføre energi mellom to asynkrone nett, i tillegg vil den også fungere som en fri bane for en ukontrollert reaktiv effektflyt. En grunnleggende modell av en 100 MW VFT, som forbinder de to kraftsystemene, er implementert i MATLAB/Simulink. En grundig undersøkelse for å forstå den reaktive effektflyten for ulike driftsforhold vil bli utført. Simuleringsresultatene indikerte betydelige mengder reaktiv effekt i maskinen ved overføring av aktiv effekt mellom de to kraftsystemene. To løsninger er undersøkt for å kompensere for det reaktive effekt behovet til den Variable Frekvens Transformatoren ved aktiv effekt overføring. De to løsningene er henholdsvis en elektromekanisk kondensatorbank og en kraftelektronikk basert STATCOM. Ved hjelp av en passiv kondensatorbank ble det reaktive effektbehovet til maskinen dekket, effektfaktoren til systemet ble forbedret og spenningen i nettet ble justert til sin nominelle verdi. Aktiv kompensasjon ved bruk av en STATCOM ble undersøkt, og det ble foreslått en spenningsreguleringsplan for implementering av STATCOMen og gls vftnoen i et kombinert system.

Preface

This Master's thesis is the finishing work of my Masters of Science degree (MSc) in Energy and Environmental Engineering with the Department of Electric Power Engineering at Norwegian University of Science and Technology (NTNU). The thesis was carried out during the spring of 2018 and is a continuation of my specialization project with the title *"Novel Frequency Converter for Low Frequency AC Offshore Transmission"*. The work covers the concept of a Variable Frequency Transformer, and assesses the reactive power capability of the machine.

Due to the novel aspect of the VFT it has proven to be challenging to find relevant literature on the topic. By invaluable help from my supervisor Prof. Olimpo Anaya-Lara at University of Strathclyde and NTNU, I have gained the knowledge I needed to carry out this work. My sincerest gratitude to him for all the help and support throughout this year.

I would like to express my sincerest gratitude to my co-supervisor, Dr. Raymundo Olguin-Torres at SINTEF for valuable help in the finishing work of this thesis. He has contributed with his expert knowledge of converters and power electronics, and I am very grateful for all his help. I would also like to thank Dr. David Campos-Gaona at University of Strathclyde for sharing his knowledge regarding this machine and for patiently taking the time to answer all my questions. I am very grateful for all the help and guidance regarding the simulation model.

One last gratitude goes to Kari-Anne Håvardsen for helping me with the tedious work of proofreading.

Trondheim, June 2018

Maren Skrunes

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Acronyms

DFIG Doubly Fed Induction Generator.

PCC Point of Common Coupling.

PWM Pulse Width Modulation.

RES Renewable Energy Resources.

RSC Rotor Side Converter.

SCC Short Circuit Capacity.

SCR Short Circuit Ratio.

STATCOM Static Synchronous Compensator.

SVC Static Var Compensator.

VFT Variable Frequency Transformer.

VSC Voltage Source Converter.

WRIM Wound Rotor Induction Machine.

Symbols

θ_s	Phase-angle of the ac voltage on the stator, with respect to a reference phasor
ω_m	Angular velocity of the induction machine
ω_r	Angular velocity of voltage induced in rotor
ω_s	Angular velocity of voltage induced in stator
ω_s	Synchronous speed of the magnetic field in rpm
ω_{rm}	Rotor mechanical speed in rpm
Ψ_a	Air-gap flux
Ψ_m	induced flux
θ_e	Electrical angle
θ_m	Mechanical angle
θ_r	Phase-angle of the ac voltage on the rotor, with respect to a reference phasor
θ_{net}	$\theta_s - (\theta_r + \theta_{rm})$
θ_{rm}	Phase-angle of the rotor with respect to stator
C	Capacitance
f_r	Electrical frequency on rotor winding
f_s	Electrical frequency on stator winding
f_{rm}	Rotor mechanical speed in electrical frequency (Hz)
i'_r	Current in the rotor, referred to stator side

I_c Current in the capacitor

i_m Magnetizing current

I_r Current in the rotor windings

I_s Current in the stator windings

i_s Current in the stator

I_{abc_m} Three phase abc-current, measured

I_{d_ref} Reference d-component of the current

I_{dq_m} dq-current

I_{dq_ref} Reference dq-current

I_{q_ref} Reference q-component of the current

L_r' Inductance at rotor side, referred to stator side

L_m Magnetizing inductance

L_r Leakage inductance of rotor winding

L_s Leakage inductance of stator winding

m modulation index

N_P Number of poles in the machine

N_r Number of windings in the rotor

n_r Mechanical speed of the rotor

N_s Number of windings in the stator

n_s Synchronous speed of the rotor

P_D Mechanical power to the torque-control drive system

P_r Electrical power in the rotor windings

P_s Electrical power in the stator windings

P_{airgap} Electrical power in the air-gap

P_{DC} Power in the DC drive motor

P_{el} Total electrical power

P_{Grid1} Active power in grid 1

P_{Grid2} Active power in grid 2

P_{L1} Electrical power in load 1

P_{L2} Electrical power in load 2

P_{mech} Mechanical power of the induction machine

p_p Number of pole pairs

P_{rotor} Active power in the rotor windings

P_{stator} Active power in the stator windings

$P_{VFT_{max}}$ Maximum power flowing through the VFT

P_{VFT} The effective active power requirement of the VFT

Q_l The combined reactive power consumed by the rotor and stator leakage reactance

Q_m The effective reactive power consumed by the magnetizing reactance

Q_r The reactive power out of the rotor

Q_s The reactive power out of the stator

Q_{Grid1} Reactive power in grid 1

Q_{Grid2} Reactive power in grid 2

Q_{rotor} Reactive power in the rotor windings

Q_{stator} Reactive power in the stator windings

Q_{tot} The effective reactive power requirement of the VFT

Q_{VFT} The effective reactive power requirement of the VFT

R_r' Resistance at rotor side, referred to stator side

R_r Resistance of rotor phase winding

R_s Resistance of stator phase winding

s Slip

S_{MVA} Short circuit MVA

$S_{N,VFT}$ Base apparent power of the VFT

T T

T_D Torque produced by the drive system

T_{mech} Mechanical torque

U_{grid} Nominal voltage in the grid

v_r' Voltage at rotor terminals, referred to stator side

V_r Voltage magnitude on rotor terminal

v_r Voltage at rotor side

V_s Voltage magnitude on stator terminal

v_s Voltage at stator side

V_2 Voltage in grid 2

V_{abc_m} Three phase abc-voltage, measured

V_{abc_ref} Reference three phase abc-voltage

V_{ac_ref} Reference AC voltage

V_{dc_m} Measured DC voltage

V_{dc_ref} Reference DC voltage

V_{DC} DC voltage

V_{dq_m} dq-voltage

V_{dq_ref} Reference dq-voltage

V_d d-component of the voltage

V_{LL} Line to line voltage

V_q q-component of the voltage

V_{rw} Voltage on rotor winding

V_{sw} Voltage on stator winding

X_{sr} Total reactance between rotor and stator terminals

Z'_r Impedance at rotor side, referred to stator side

Z_m Magnetizing impedance

Z_s Stator inductance

Z_{grid} Grid impedance

Chapter 1

Introduction

1.1 Motivation and background

In recent years we have witnessed a progressive development of the electric power system. However, as the population grows, combined with increased welfare and industrialization of formerly underdeveloped countries, the need for energy in the future will increase rapidly. Additionally, the scarcity of fossil resources will impact the energy development, and many countries face this challenge by expanding their renewable energy production. The increased demand for secure and reliable energy combined with an expansion of Renewable Energy Resources (RES) and Distributed Energy Resources (DER) are aspects causing concerns for the future. Implementing RES is not straightforward and system stability is not granted. The area of generation is constrained by the availability of the source and may be located far away from the transmission system [1]. To be able to utilize the available power sources, deliver quality power, and to maintain an acceptable price range of electricity, one solution is to expand the interconnections of the worlds power supply system. Including inter-regional and international connections, as well as asynchronous interconnections. The majority of the power system networks in the world today operate at a nominal frequency of either 50 or 60 Hz. Merging of adjacent power networks is an evolving trend in the worlds electric power system today, and the ongoing research on the field is of interest worldwide. These interconnections are necessary for power delivery and to pool power plants and loads. Transmission interconnections provide the advantage of including a diversity of loads and available sources, making it possible to supply quality power to the loads at a minimum prize [2]. HVDC technology has proven to be a viable alternative for interconnecting both synchronous and asynchronous power systems. However, in a weak grid interconnection, the HVDC-technology does not function as required. In recent years the VFT is proposed as a novel frequency converter for providing bi-directional power flow control between asynchronous systems.

High Voltage DC-link

HVDC technology is commonly used for interconnection of asynchronous networks. This can be achieved by a back-to-back converter station, where one side operates as an inverter and the other side as a converter. The inverter and converter are linked by a DC-link. The power flow is regulated by controlling the converter valve group firing angle (in the case of the classical LCC-HVDC) [3]. The HVDC besed on Voltage Source Converter (VSC) provides full control of the active and reactive power being transferred, and that the fault current limitation is rapid. It is conventional for long distance transmission where the DC-link can be extended in the form of a transmission line or cable [4]. However, the high cost of constructing the converter stations is a crucial disadvantage. The HVDC technology is demanding and costly. The conventional HVDC-link is limited to a point-to-point connection and a multiterminal, despite all the research effort, is not a mature technology.

Variable Frequency Transformer

The Variable Frequency Transformer was first introduced by GE Energy as a novel alternative to control power flow between asynchronous networks and in 2004 the world's first VFT started commercial operation [5]. It is located at the Langlois substation, interconnecting the New York (USA) and the Hydro-Quebec (Canada) systems [6]. The operation and mechanical design of the VFT is based on well-known technologies of the rotary transformer, variable speed-drive system, and DC-motor [7]. The diversity of the VFT lies in its ability to interconnect both synchronous and asynchronous power systems and control the power flow between them. In addition to power flow control, the VFT can also be a source of inertia and frequency droop control [8]. The fundamental operation of a VFT is similar to the variable phase-shifting transformer, which can operate at an adjustable phase angle [9]. Figure 1.1 illustrates a conceptual system diagram of the VFT. The core of the machine is a rotary transformer where stator and rotor three-phase windings are connected to separate networks. Electrical power is exchanged through the air gap by magnetic coupling [10]. The wound rotor shaft is connected to an external DC-drive motor with the function of providing the necessary torque for a smooth power flow through the machine. The variable-speed drive system and DC motor are controlled to provide frequency matching torque in either direction, thus controlling magnitude and direction of the active power flow. Previous studies of the VFT have shown its benefits with respect to harmonics, fault ride through and stability. Reference [11] demonstrates the VFTs compatibility with nearby grid components such as generation, voltage support devices and phase shifters. HVDC converters act faster than the VFT, milliseconds compared to seconds, this is due to the power electronics [3]. However, the response of the VFT provides the advantage of being well damped [4]. As a consequence of the power electronic converters in the HVDC-technology, there will be a power limitation in the interconnection. As opposed to the HVDC and FACTS equipment, the VFT does not produce harmonics [12].

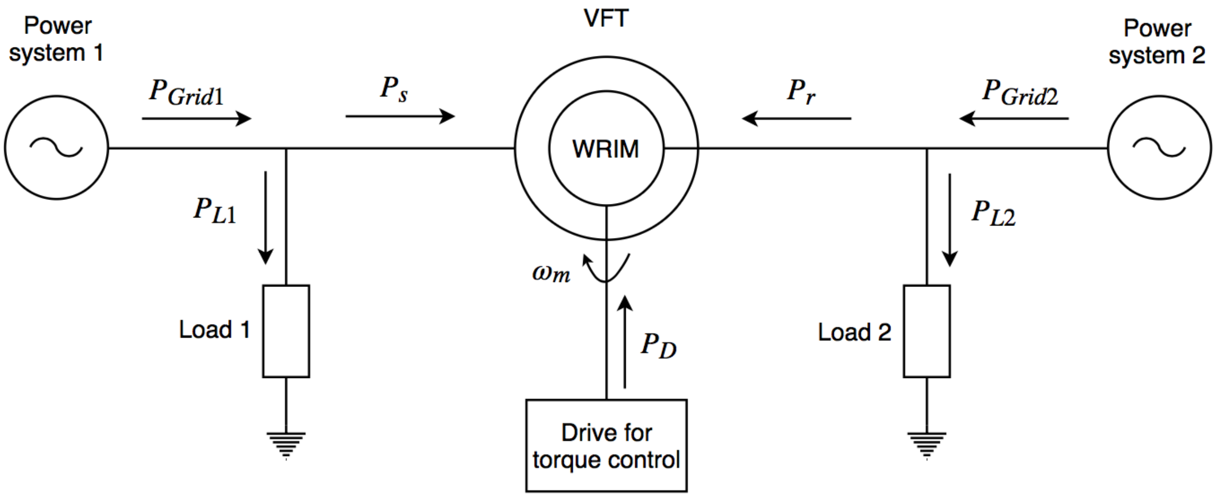

Figure 1.1: VFT System Configuration.

The two alternatives presented, namely HVDC and VFT are viable for different controllable interconnection solutions. Table 1.1 presents a comparison of the VFT and the VSC-based HVDC [13].

Table 1.1: A comparison of the two technologies, VFT and VSC HVDC, used as interconnection between synchronous and asynchronous AC grids. ✓: best in class, ✗: unable to perform, blank: system standard

	VFT	**VSC HVDC**
High Efficiency	✓	
High Availability	✓	✓
Low Complexity	✓	
Control of Reactive power	✗	✓
Black Start Capability	✓	
Low Control Interactions	✓	✗
Low Harmonic Generation	✓	✗
Easy Interaction with Grid Components	✓	✗
Bump-less Startup	✓	✓
Reaction Time to Control Command		✓
Based on well Established Technology	✓	✗
Small Space Requirements	✓	✗

The novel frequency transformer has so far proven to be a feasible alternative for interconnecting both synchronous and asynchronous power systems. Due to the relative new concept, the VFT is not elaborated in detail in literature, thus *the aim of this thesis will be to investigate the fundamentals and the basic operation of a VFT with particular emphasis on understanding the reactive power characteristics*. The VFT provides active power exchange between the two connected networks and it also enables a reactive power exchange through the machine, which are not fully controllable. As for any other AC system, the reactive power flowing through the VFT is determined by the voltage on each side of the machine and the impedance between the two voltages. The limitations of reactive power flow control is the reason why the VFT cannot provide perfect isolation between the connected grids. Uncontrolled amounts of reactive power may have a negative impact on power quality and system stability. Although active and reactive power is closely related, the reactive power issue of the VFT is not elaborated in current literature, and there seems to be lack of research on the topic. *The reactive power capacity of the Variable Frequency Transformer will therefor be the focus for the remainder of the thesis*.

1.2 Objectives

The main objectives of this thesis will be:

1. To provide a basic understanding of the operation of the VFT.
2. To develop a simulation model comprising of two asynchronous systems interfaced by a 100 MW VFT.
3. To identify the reactive power requirement of the VFT as an interconnection between both synchronous and asynchronous electrical power systems.
4. To assess the reactive power capacity of the VFT when voltage fluctuations are present.
5. To investigate different reactive power compensation schemes for the VFT.

1.3 Scope of Work

The aim of this thesis is to examine the concept and basic operation of a VFT, with a focus on the reactive power capability. Therefore, the thesis does not emphasize the practice for obtaining optimal operating conditions, nor does it provide results from actual circumstances. Case studies are used to demonstrate concepts and provide a basic understanding of the VFT under various operating scenarios aiming to characterize the reactive power requirements. Throughout the thesis, there will be a focus on the matter of reactive power in the system. Once having understood the reactive power flow, the thesis will investigate reactive compensation. The static compensation of a capacitor bank will be implemented and assessed in the system model. A dynamic approach using a STATCOM will be investigated on a theoretical basis. The STATCOM will not be analyzed by simulations, as simulations as this was considered out of scope for the duration of the project. However, guidelines are provided for future work to further developed the test model to accommodate the incorporation of the STATCOM. The work comprises the following:

- A literature study of the fundamentals of the Variable Frequency Transformer, where some sections are based on the work carried out in the specialization project. The reactive power issue is emphasized.
- A development of a 100 MW VFT system combined with reactive power compensators assembled in the MATLAB/Simulink simulation tool.
- A detailed study assessing the basic concept of the VFT.
- An analysis of the reactive power capability of the VFT under different operating conditions.
- An investigation of possible reactive power compensators to combine with the VFT.

1.4 Outline

Chapter 1 - *Introduction*, provides the motivation for the work performed in this thesis, and a background study of the state of the art technology.

Chapter 2 - *Comparative analysis of the VFT and DFIG*, presents a comparative analysis of the VFT and Doubly Fed Induction Generator (DFIG) technologies. The aim of this chapter is to emphasize similarities between the two machines, and thus to set the basis for understanding the fundamentals of the VFT which are covered in chapter 3.

Chapter 3 - *Variable Frequency Fundamentals*, gives an extensive description of the VFT. The concept of operation is explained in terms of steady state equations. A study case is simulated in MATLAB/Simulink. Sections which are adapted from the Specialization project:

- Section 3.1
- Section 3.3

Chapter 4 - *Reactive Power Requirement of a VFT*, investigates the reactive power requirement of the machine under different operating conditions.

Chapter 5 - *VFT Reactive Power Compensation using a STATCOM*, presents an alternative system of a VFT in combination with a STATCOM.

Chapter 6 - *Summary and Conclusion*, provides a summarizing discussion of the simulation results obtained in the different study cases. The chapter also concludes the discussed results and findings obtained in the work an it suggests relevant activities for future work.

Chapter 2

Comparative Analysis of the VFT and the DFIG

The variable frequency transformer is a relatively new concept and the first VFT started commercial operation in 2004 [7]. Although the conceptual utilization of this machine is new, the VFT is composed of well-known hydro generator, dc motor, and variable-speed drive technology. To understand the operation and construction of a VFT it can be useful to investigate the principles of the DFIG because of the many similar aspects between the two machines including slip, power flow, and mechanical design. It should be emphasized that the topics covered in this chapter are only to give an introduction to the VFT and the analogies to the DFIG. An extensive investigation of the VFT concept will be presented in Chapter 3.

2.1 DFIG fundamentals and principle of operation

A common configuration of a DFIG wind turbine is presented in fig. 2.1. The DFIG consists of an induction generator with a wound rotor. A back-to-back power converter connects the rotor windings via slip ring configuration to the grid. The rotor shaft is connected to the turbine through a gearbox and the stator is directly coupled to the grid. The DFIG is currently the dominant generator technology in wind turbines due to its ability to operate at over a wide wind speed range [14]. Thus, the generator is able to operate at a variable rotational speed.

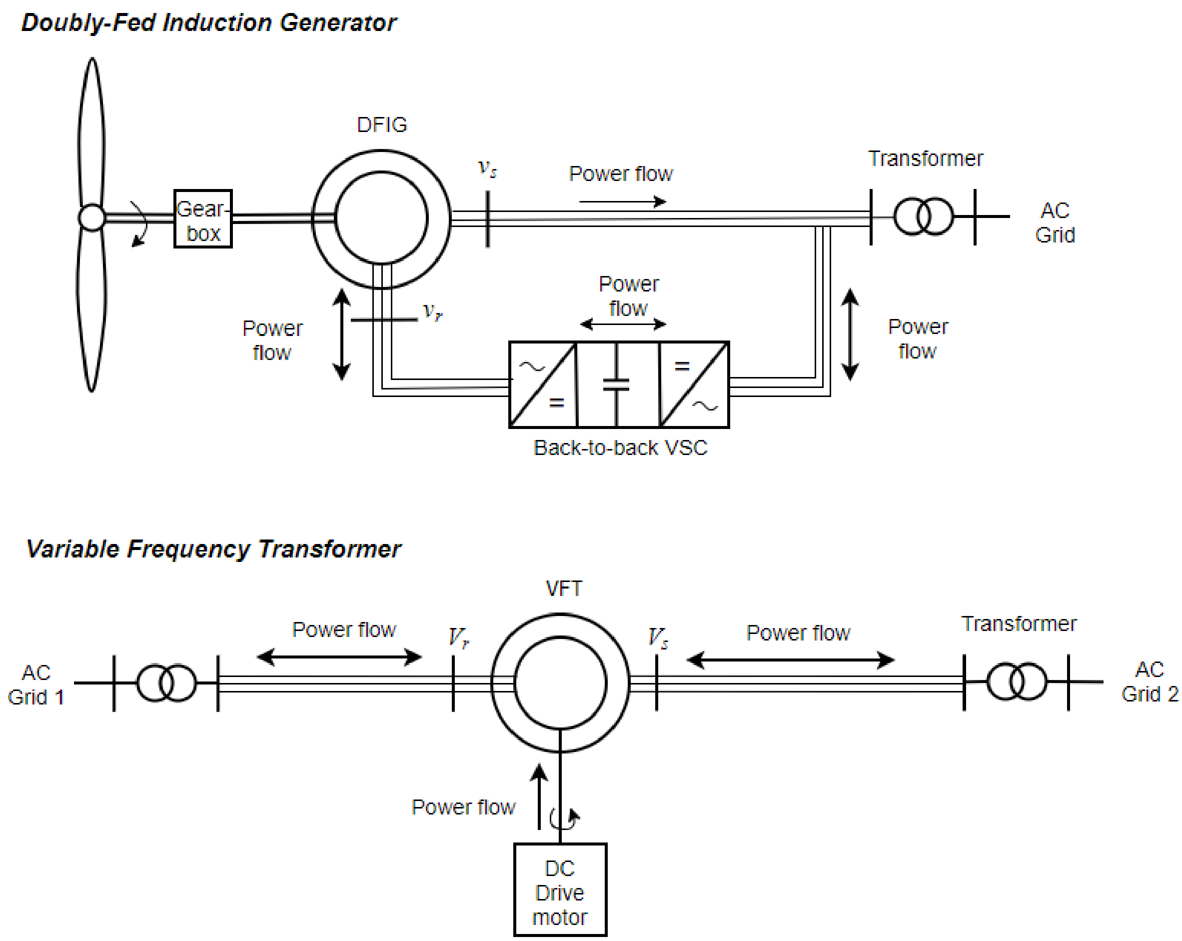

Figure 2.1: Doubly Fed Induction Generator connected to a Wind Turbine, and a Variable Frequency Transformer interconnecting two grids

In a DFIG configuration both the stator and rotor windings are linked to the electrical grid, hence the term ”doubly fed”. The rotor windings are excited with a three-phase current, which induces a rotor magnetic field. When the two magnetic fields of the stator and rotor interacts a torque is developed [14]. The strength and angular position of the two magnetic fields determines the magnitude of the torque. The magnetic fields of the rotor and stator establish a pair of magnet poles. The torque is produced by magnetic attraction between magnet poles of opposite polarity. To understand the different magnetic fields in an induction machine it can be useful to evaluate the multi-pole pair machine as the two pole machine due to symmetry. The voltage induced in the stator terminals of a multi-pole pair machine will have a frequency which is related to the actual rotation of the rotor given by [15] as:

$$\theta_e = \theta_m \cdot p_p \tag{2.1}$$

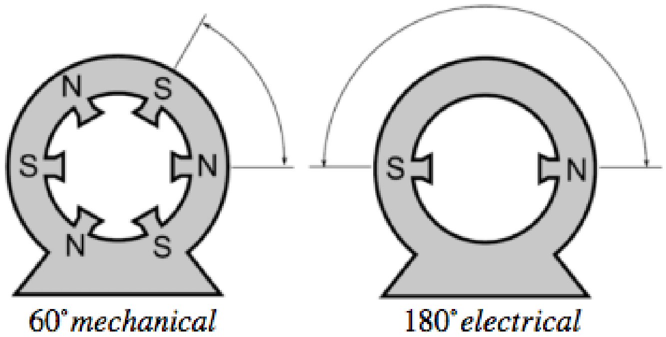

Figure 2.2: Multi- and two-pole machine [16]

Where θ_e and θ_m is the electrical angle and mechanical angle respectively. p_p is the number of pole pairs. This means that for a four pole machine (two pole pairs) the electrical frequency of the induced voltage, θ_e, will be twice the size of the mechanical angle.

2.2 Slip

The rotor speed is an important factor for determining the characteristics of the DFIG as electromechanical characteristics of the generator is strongly dependent on the on the slip and therefore the rotor speed [17]. In an induction machine, the slip is defined as the difference between synchronous speed and operating speed. It can also be defined as the difference between the synchronous speed of the magnetic field and the rotating speed of the rotor shaft [14]. The slip, s, can be expressed as:

$$s = \frac{n_s - n_r}{n_s} \tag{2.2}$$

where n_s is the synchronous speed and n_r is the mechanical speed of the rotor. The slip can also be defined in terms of angular speed [18].

$$s = \frac{\omega_s - \omega_r}{\omega_s} \tag{2.3}$$

Here ω_s is the synchronous speed in rpm and ω_r is the rotor speed in rpm. The slip can be either positive or negative, depending on whether the shaft speed is higher or lower than stator magnetic field. The properties of the slip are given as [19]:

- s $>$ 0 : Sub-synchronous operation
- s $<$ 0 : Super-synchronous operation
- s = 0 : Synchronous operation

When the DFIG operates with a positive slip the synchronous speed is higher than the rotational speed. In this operational state, which is known as the sub-synchronous mode, power is supplied to the grid only through the stator [17]. As illustrated in fig. 2.3, in sub-synchronous mode the fraction of active power flowing through the rotor depends on the slip of the generator. This power is supplied from the grid to the rotor. A negative slip corresponds to the super-synchronous operation. In this mode, the rotational speed of the rotor is higher than the synchronous speed and power is supplied to the grid through both the stator and rotor [17]. The active power flowing from the rotor to the grid depends on the slip of the machine. Figure 2.3 illustrates the sub-synchronous and super-synchronous operation of the DFIG, in both operations P_r is nearly proportional to the slip. A DFIG operating in a synchronous mode is when the rotor and stator field are synchronized, and at this point, the slip is zero and no flux is induced, hence no power will flow [15].

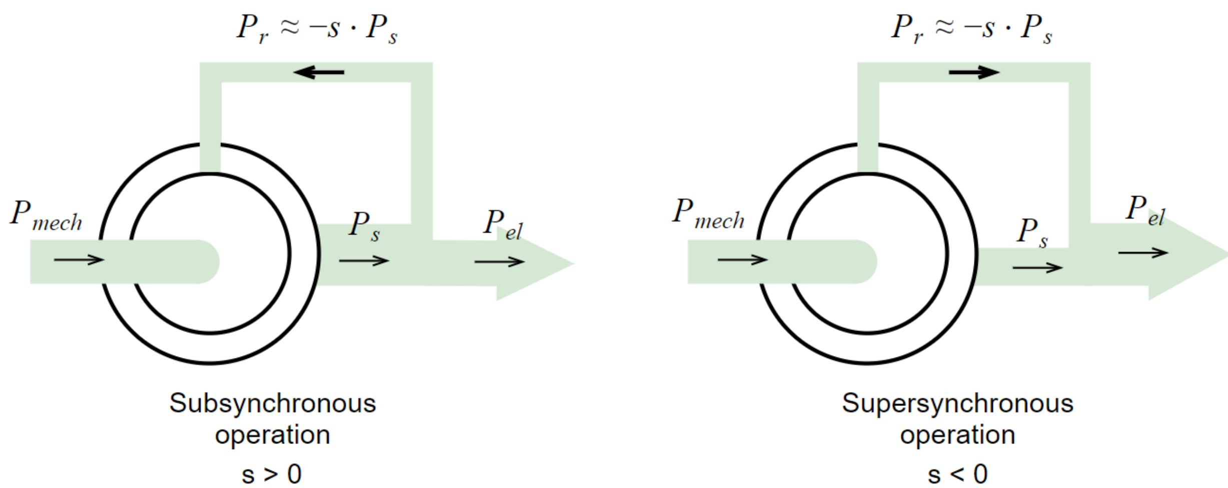

Figure 2.3: Sub-synchronous and Super-synchronous operation of a DFIG [17]. P_{mech} is the mechanical power in the rotor shaft, P_r is the active power in the rotor windings, P_s is the active power in the stator windings, and P_{el} is the total power flowing to the network.

A VFT is able to transfer power between synchronous grids, even though the slip is zero, due to phase shifting operation [7]. The frequency of the voltages induced in the stator and in the rotor are related to the mechanical speed as:

$$\omega_m = \omega_s \pm \omega_r \tag{2.4}$$

The angular velocity of the machine is denoted as ω_m. ω_s and ω_r can also be denoted as the angular velocity of the voltage induced in the stator and rotor, respectively. The stator side of the DFIG is connected to the grid, hence the energizing voltage will be stable and the frequency fixed. The shaft is connected to the wind turbine through a gearbox, and the wound rotor windings are normally connected via slip rings and a back-to-back VSC to the grid, as shown in fig 2.1. The Rotor Side Converter (RSC) supplies the rotor circuit with a voltage, v_r, at variable frequency and magnitude to achieve the desired speed, torque or power ratings [1]. The purpose of voltage control at the rotor terminals is to control the current flowing in the rotor windings, and thus the rotor flux. This way the rotor flux position is optimally oriented with respect to the stator flux such that the desired torque is generated at the shaft of the machine [14]. By varying the rotor frequency, thus varying the slip, the generator can be operated at different speeds. A DIFG is often used for wind power applications, this is mainly due to its ability to operate over a wide wind speed range [20]. In both the VFT and the DFIG, the stator side voltage and frequency are fixed. The fixed frequency of the voltage can be calculated in terms of mechanical angular speed by [14]:

$$\omega_s = \frac{2 \cdot \pi \cdot f_s}{p_p}[rad/s] \tag{2.5}$$

$$n_s = \frac{60 \cdot f_s}{p_p} \quad [rpm] \tag{2.6}$$

Equation 2.6 represents the synchronous speed of the rotor. f_s is the electrical frequency of the applied stator voltage and p_p is the number of pole pairs. In the case where the rotor side is open circuited and the rotor is locked (standstill), a voltage will be generated at the rotor terminals due to excitation of the stator. In this case, the frequency of the rotor side voltage will be equal to the frequency of the applied voltage, due to the slip being equal to 1. When the rotor speeds up, it operates in a sub-synchronous mode, which means that the rotor speed is lower than the synchronous speed of the machine. In this mode, the RSC operates as an inverter, and power is applied to the rotor from the grid. In the DFIG the frequency at the output terminals of the rotor will start to decrease as the rotor accelerates towards synchronous speed. When the rotor speed is at synchronous speed, the rotor frequency, and the slip is zero. As the rotor accelerates beyond synchronous speed the machine operates in a super-synchronous mode, and the frequency of the rotor voltage starts increasing. In this case, the frequency has opposite phase sequence to the sub-synchronous mode. The frequency of the voltage at the rotor terminals is [14]:

$$f_r = s \cdot f_s \tag{2.7}$$

In a VFT both the rotor and stator voltages and frequencies are more or less fixed because the stator and rotor windings are directly connected to each separate network. However, equations 2.1-2.7 are also valid for a VFT when the two grids operate at different frequency [7] due to the relationship of the frequency and slip being the same for a VFT and a DFIG.

2.3 Active Power and Torque

Currents flowing in the rotor windings produce a rotor magnetic field, which interacts with the magnetic field set up by the stator currents, and torque is produced. By calculating the power absorbed, or generated, by the rotor resistance component $\frac{R_r(1-s)}{s}$, it is possible to obtain the mechanical torque generated by the machine. The mechanical power of the machine is [14]:

$$P_{mech} = 3|I_r|^2\left(\frac{1-s}{s}\right)R_r \tag{2.8}$$

In an ideal induction machine, the losses in the windings due to resistance and leakage induction can be ignored. Thus, the simplified expression for the mechanical torque is:

$$T_{mech} = 3|I_r|^2\left(\frac{1-s}{s}\right)\frac{R_r}{\omega_m} \tag{2.9}$$

As

$$\omega_m = \frac{(1-s)\omega_s}{p} \tag{2.10}$$

$$\psi_m = L_m i_m = \frac{V_s}{\omega_s} = \frac{|i_r|R_r}{s\omega_s} \tag{2.11}$$

$$T_{mech} = 3|I_r|^2\left(\frac{1-s}{s}\right)\frac{R_r}{\omega_s} = 3p\frac{|i_r|R_r}{s\omega_s}|i_r| = 3p\psi_m|i_r| \tag{2.12}$$

The mechanical torque can be expressed in terms of stator generated flux and the magnitude of the rotor current. In the DFIG system, the torque is controlled by calculating the magnitude and position of the stator generated flux, and regulating the rotor currents. The rotor currents are regulated in a position such that they are normal to the stator flux, and with a magnitude that provides the desired torque. In a VFT neither the stator or rotor currents can be regulated, and the torque is directly generated by a DC drive motor.

DFIG

Figure 2.4 represents the steady-state relationship between the mechanical power and stator and rotor electrical power in a DFIG. P_m is the mechanical power generated by the turbine, P_r is the power delivered by the rotor to the converter. It should be noticed that P_r flows in both directions depending on the slip of the machine, hence the super- or sub-synchronous mode. The power in the generator air gap is represented by P_{AirGap}, and P_s is the power delivered by the stator. By neglecting stator cu losses and iron losses the air gap power is [20]:

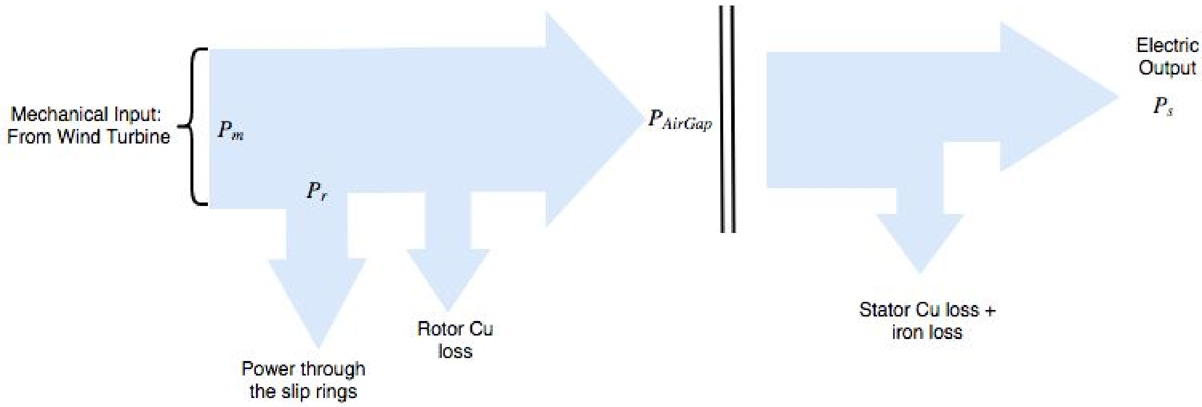

Figure 2.4: Power flow DFIG

$$P_{airgap} = P_s \tag{2.13}$$

And by neglecting rotor cu losses the power through the air gap can be expressed by:

$$P_{airgap} = P_m - P_r \tag{2.14}$$

Combining equations 2.13 and 2.14 we get an expression for the stator power as:

$$P_s = P_m - P_r \tag{2.15}$$

Introducing torque in equation 2.15 and rearranging the expression:

$$P_r = -T(\omega_s - \omega_r) \tag{2.16}$$

Where $P_m = T\omega_r$ and $P_s = T\omega_s$. Implementing the definition of the slip from eq. 2.3, the stator and rotor power can be related as:

$$P_r = -sT\omega_s = -sP_s \tag{2.17}$$

The total power delivered to the grid, P_g is:

$$P_g = P_r + P_s \tag{2.18}$$

VFT

Equations (2.13)-(2.18) can be used in the steady-state representation of the VFT as well. The only difference is the direction of the power flow in the rotor side, as the power in a VFT is transferred from one side to the other. This is illustrated in fig. 2.5 where the power through the rotor P_r is added to the mechanical power from the DC drive motor. Thus eq. (2.14) is changed to:

$$P_{airgap} = P_m + P_r \tag{2.19}$$

which results in P_r being equal to:

$$P_r = sP_s \tag{2.20}$$

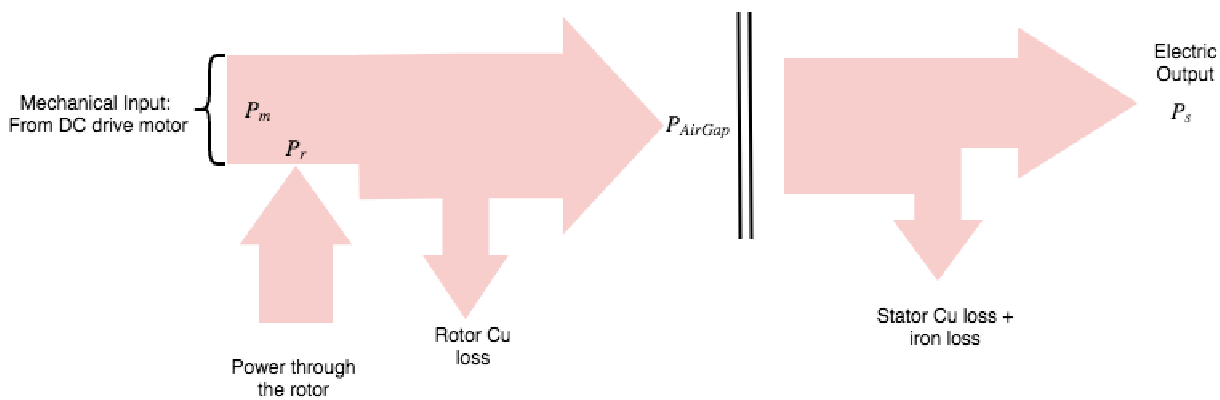

Figure 2.5: Power flow VFT

The wound rotor windings in a DFIG are normally connected via slip rings and a back-to-back VSC to the grid. The rotor power in a DFIG is usually limited to approximately 30% of the nominal generator power due to losses in the power converter [21]. In a VFT there is no power converter, hence no limit for the rotor power. Both DFIG and VFT is based on a rotary transformer, and as previously mentioned, the slip is an important factor. A DFIG operating with a positive slip, also known as sub-synchronous mode, can be compared to the VFT operation when power is floating from the rotor side to the stator side, as presented in fig. 2.5.

2.4 Reactive Power

Both the VFT and DFIG is as mentioned based on the technology of the induction machine. The induction machine consumes reactive power, due to magnetizing currents flowing in the windings. These magnetizing currents set up a rotating magnetic field, which the machine requires for energy conversion. The machine absorbs reactive power to maintain the magnetic field.

DFIG

The reactive power capability of the DFIG depends mainly on the limit of the three design parameters, including rotor voltage, rotor current, and stator current [17]. The stator voltage is fixed by the grid, and not influenced by the wind turbine. The limits of the rotor voltage and current depend on the design of the generator and the power converter [17]. The power electronic VSC connected to the rotor of the DFIG consists of a Rotor Side Converter (RSC) and a Grid Side Converter (GSC) which are connected back-to-back, see fig. 2.1. The two converters are linked via a common dc-bus, used as energy storage. The main objective of the rotor side converter is to modify the rotor currents to control the speed of the wind turbine and thus, the reactive power consumption [18]. The controllable reactive power fed to the rotor is amplified on the stator-side [21]. The main objective for the grid side converter is to keep the voltage variations (ripple) in the dc-link voltage small, regardless of the magnitude and direction of the power flowing through the converter [14]. A more or less constant dc-link voltage is required for correct operation of the rotor side converter. The grid side converter can also provide some reactive power support to the grid [18].

VFT

As illustrated in fig. 2.1 both rotor side and stator side of the VFT are connected to an AC grid. Hence, v_r and v_s are given by the grids operating conditions and is not affected by the design of the VFT. However, the exchange of reactive power between the two grids, through the VFT, strongly depends on the voltages in each side of the machine. Similar to the conventional power system, the reactive power flow in a VFT is determined by the voltage difference between the terminals of the machine and the impedance between them. The VFT is unable to control the reactive power flow alone, hence additional reactive power support is required for this operation. The VFT reactive power topic will be addressed further in chapter 4.

2.5 Control

DFIG

As previously mentioned the DFIG can operate over a wide wind speed range to obtain maximum power output from the wind turbine. The generator's rotor must be able to operate at a variable rotational speed. The variable rotational speed operation of the DFIG is obtained by injecting a controllable voltage into the rotor at slip frequency [22]. The controllable voltage is supplied by the RSC, with the purpose to control the rotor currents. This way the rotor flux position is optimally oriented with respect to the stator flux and the required torque is developed at the shaft of the machine [14].

VFT

Also the VFT can operate at variable rotational speeds. However, in a VFT the voltages on both stator and rotor side are fixed by the connected grids. Thus the VFT cannot be controlled in the same way as the DFIG, where the rotor side voltage and frequency are regulated to obtain desired torque. In a VFT the torque is directly connected to a DC drive motor and a variable speed drive system, see fig. 2.1. The drive motor is used to provide regulated torque to have a continuous rotation in either direction to provide frequency matching [7]. An extended explanation of the control systems of the VFT will be given in section 3.4.

2.6 Mechanical design

The mechanical design of both the machines is based on a rotary transformer. The stator and rotor are constructed with three-phase windings and the rotor shaft is connected to an external source. The DFIG rotor shaft can be connected to for example a wind turbine or a steam turbine, while the VFT is connected to a DC drive motor. The rotor is located inside the stator, and power is being exchanged through the air-gap by the principle of induction. Due to currents flowing in the rotor windings flux is induced in the stator. Thus, the slip plays an important role in both the DFIG and the VFT. The conventional transformer and both the VFT and DFIG composes similarities including the exchange of power and some design aspects. However, normal operation of a conventional transformer is to transform voltages up/down. In a VFT the voltages are fixed on both sides, and the frequencies can fluctuate. Its main operation is to transform the frequency up/down. Table 2.1 presents some of the aspects where the VFT can be compared to the conventional transformer.

Table 2.1: VFT compared to the conventional transformer

VFT	**Convntional Transformer**
Transform frequency	Transform voltage
Air gap	Ferromagnetic material
Stator and rotor	Primary and secondary winding
1:s, where s is slip frequency	1:n, where n is voltage transfer ratio

2.7 Summary

This chapter includes analogies between the VFT and dfig, and also the VFT and a transformer. Table 2.2 lists some of the main findings.

Table 2.2: A summary including similarities and inequities between the VFT and DFIG

	VFT	**DFIG**
External source connected to the rotor shaft	DC-motor connected to a variable speed drive system	Usually a wind turbine
Slip	$s = \frac{\omega_s - \omega_r}{\omega_s}$	$s = \frac{\omega_s - \omega_r}{\omega_s}$
If s=1 (Synchronous mode)	Adjust the phase angle by means of the DC-drive motor to be able to transfer power	No power will flow
Mechanical design	Rotational transformer which is doubly fed	Doubly fed induction generator
3-phase stator windings	Connected to a power system, thus voltage is fixed	Connected to a power system, thus voltage is fixe
3-phase rotor windings	Connected to a power system, thus voltage is fixed. ”No” limitation in power flow. $P_r = s \cdot Ps$	Connected to a power electronic converter. The converter limits the power to 30 %.
Power flow control	By means of the DC-drive system torque is applied to the rotor shaft to adjust rotor position with respect to the stator, and by this controlling active power flow	Inject a controllable voltage at the rotor terminal, to regulate rotor currents, thus regulating the flux fields
Reactive Power	• Requires reactive power to build magnetic flux fields in the air gap. • Additional reactive power will flow during active power transfer. • Not controlled by the VFT alone • Supplied by the two interconnected grids, or by additional reactive power compensators.	Requires reactive power to build magnetic flux fields in the air gap. Reactive power is supplied and controlled by the power electronic converter.

Chapter 3

Variable Frequency Transformer Fundamentals

Parts of this chapter is based on the work titled *”Novel Frequency Converter for Low Frequency AC Offshore Transmission”* [23] carried out by the author of this thesis during the autumn of 2017. This includes the following sections:

- Parts of section 3.1
- Section 3.3

The Variable Frequency Transformer is presented as a novel alternative for interconnection of asynchronous power systems. The VFT was first introduced by General Electric Company [24], and in 2004 the first VFT started commercial operation at Langlois substation connecting the Hydro-Québec and the New York grid [6]. A VFT is a controllable bidirectional transmission device that can transfer power between asynchronous power grids. The machine is based on the conventional technology of a rotary transformer and hydro generator [25].

3.1 VFT Concept

A Variable Frequency Transformer is a doubly fed induction machine used to connect two separate systems carrying alternating current at potentially different frequencies [7]. Although the concept is relatively new, the VFT is based on a combination of the well-established transformer and hydro-generator technologies. Essentially it is a phase-shifting transformer able to operate at an adjustable phase angle. The core of the VFT is a rotary transformer consisting of a three-phase rotor and a three-phase stator [8]. The two networks are electrically coupled to the rotor windings and stator windings respectively. Electrical power is exchanged when current is flowing in the windings and a magnetic field is induced in the air-gap between the stator and the rotor. Hence, the principle of the VFT is based on purely mutual induction as there is no electrical connection between the two networks [9].

The active power flow through a VFT is proportional to the phase angle difference between the stator and the rotor. The magnitude of phase shift required for a given power transfer is determined by the impedance of the rotary transformer and the network connected [25]. By means of a DC motor, which is controlled by a variable speed drive system, torque is applied to the rotor to regulate rotor position with respect to the stator. By regulating the rotor position, hence the phase angle, it is possible to control the magnitude and direction of the power flowing through the VFT. The amount of reactive power flowing through the VFT is determined by the difference in voltage magnitude of the two sides, and the series impedance of the transformer [7].

The rotor intrinsically positions itself to follow the phase angle difference introduced by the two networks. If the systems are operating at different frequencies the rotor will move continuously with a rotational speed proportional to the frequency difference to obtain synchronization between stator and rotor fluxes in the air-gap. If however, the two networks are in synchronism, the normal operating velocity is zero and the VFT works as a phase-shifting transformer. In synchronous mode no power is transmitted as the rotor of the VFT persist in a position where the rotor and stator voltage are in phase with related systems. In order to transfer power between the two synchronous networks, it is necessary to apply an external torque to the rotor shaft. The torque turns the rotor in the position where the power flow demand is satisfied. The direction of the applied torque determines the direction of the power flow. The drive motor system is designed to continuously produce torque while at standstill. If no torque is supplied, no power will flow through the VFT [25].

During normal operation, the VFT will be introduced to voltage and frequency deviations as a consequence of disturbances in the two power networks. In order to keep a constant power flow through the VFT during frequency fluctuations the control system must act constantly to maintain the relative rotor position with respect to the stator. A closed-loop regulator works to keep the power transfer at a given setpoint. The power regulator measures the power flow and compares it with the setpoint value, and according to the error, it adjusts the amount and direction of torque applied to the rotor [25]. This will be further explained in section 3.4

3.2 Mechanical design of the VFT

When a VFT is used as an interconnection between two grids, standard substation equipment such as circuit breakers, transformers, switchgear, control center etc. are also required [26]. An overview of a VFT substation is illustrated in fig. 3.1. This is standard equipment and will not be focused on in this thesis. The core technology of the VFT is based on a rotary transformer with three-phase windings on both the stator and the rotor. The main components of the VFT is the rotating transformer, the DC drive motor, and the collector system. The system components in a VFT are presented and illustrated in fig. 3.2.

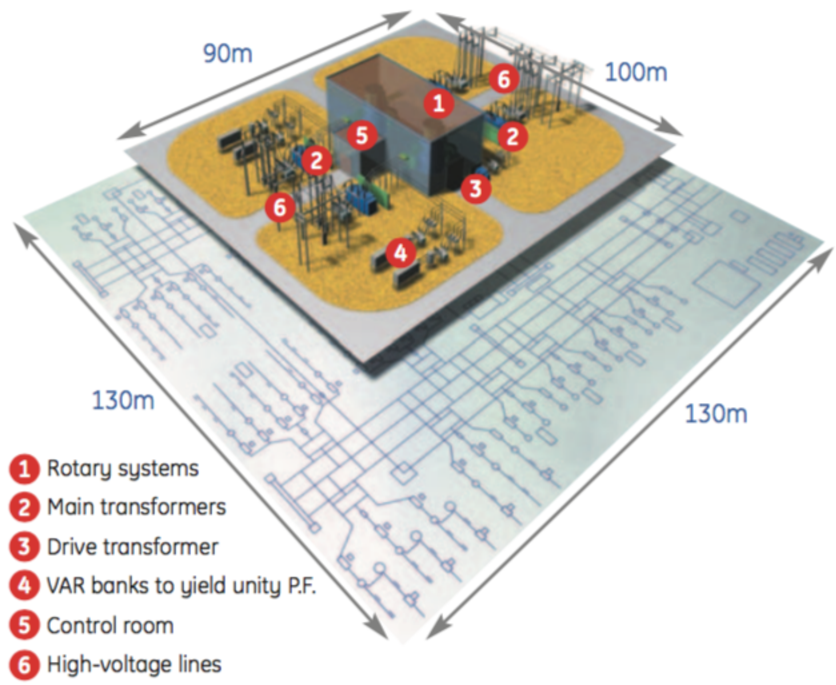

Figure 3.1: VFT substation [27]

3.2.1 Rotary Transformer

The rotary transformer of a VFT consists of a wound rotor located within a stator. The VFT is doubly fed, which means that both the rotor and the stator windings are connected to separate networks. The winding configuration is a three phase four pole arrangement. One network is connected to the three-phase stator windings via a Step-up transformer, while the other network is connected to the three-phase rotor windings, also through a Step-up transformer.

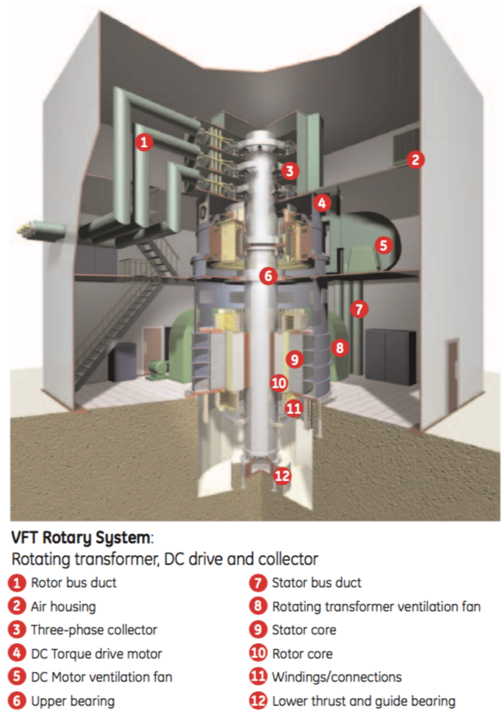

Figure 3.2: System components in a VFT [27]

3.2.2 Three-phase Collector System

By means of the three-phase collector system located on the top of the rotating structure [7], current is conducted between the rotor windings and its stationary bus duct. The collector construction consists of a shaft and slip rings arrangement. Slip rings are necessary for the rotor to run freely while connected to a network. The slip rings are normally made of copper, with carbon brushes on top [2]. The rotor windings are linked to the collector rings via a three-phase bus placed inside the hollow shaft. The self-cooling capability of the rotary assembly is low, hence forced-air cooling is necessary [28]. The stator of a VFT is practically identical to the stator used in hydro generators [11], and on the surface, they look the same. The VFT is comparable with large electrical generators which provide a significant amount of inertia. The high amount of inertia might support the grid in maintaining stable operation during events [29].

3.2.3 DC-drive motor

The drive motor used in a VFT is a conventional DC-motor which is connected to the rotor shaft, and its main task is to provide torque to the rotor. The DC motor operates with a variable speed drive system which is used to match the frequency difference between the rotor and stator field by regulating the magnitude and direction of the applied torque. The power flowing through the VFT is proportional to the direction and magnitude of applied torque. If the systems are in synchronism no power will flow through the rotating transformer if no torque is applied. This can be justified by eq. 3.8 and eq. 3.9. The DC motor and the variable-speed drive system is designed to continuously produce torque while the rotor is at standstill [7].

3.3 VFT Operation

In this section basic equations are presented to provide an understanding of the operation and control of the VFT, the equations are obtained from [9, 26, 30, 31]. The model used for power analysis is shown in fig. 3.3, and associated phasor diagram is presented in fig. 3.4. The VFT is represented by a Wound Rotor Induction Machine (WRIM) which is doubly fed. Thus, the stator an rotor windings are connected to each separate networks. Power system 1 is connected to the stator, and power system 2 is connected to the rotor. A drive motor, used to apply torque, is mechanically connected to the rotor of the VFT. A control system regulates the applied torque to adjust the rotor position relative to the stator, thereby controlling the power flowing through the VFT.

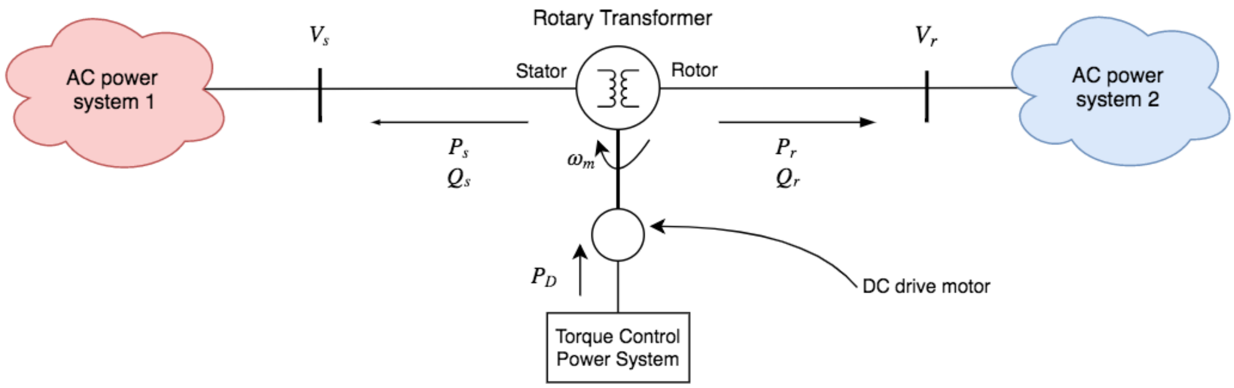

Figure 3.3: Power Flow in a VFT

3.3.1 Power Regulation

The power flowing through the VFT, P_{VFT}, can be approximated by:

$$
\begin{aligned}
P_{VFT} &= \frac{V_s V_r}{X_{sr}} sin(\theta_s - (\theta_r + \theta_{rm})) \\
P_{VFT} &= \frac{V_s V_r}{X_{sr}} sin(\theta_{net})
\end{aligned}
\tag{3.1}
$$

Where V_s and V_r are the voltage magnitude on stator and rotor terminal, respectively, and the reactance between the stator and rotor is denoted X_{sr}. θ represents the different phase angles with respect to a fixed reference phasor. The phasor diagram is presented in fig. 3.4. θ_s and θ_r is the phase-angle of the ac voltage on the stator and rotor, respectively. The phase-angle θ_{rm} is the angle of the rotor with respect to stator.

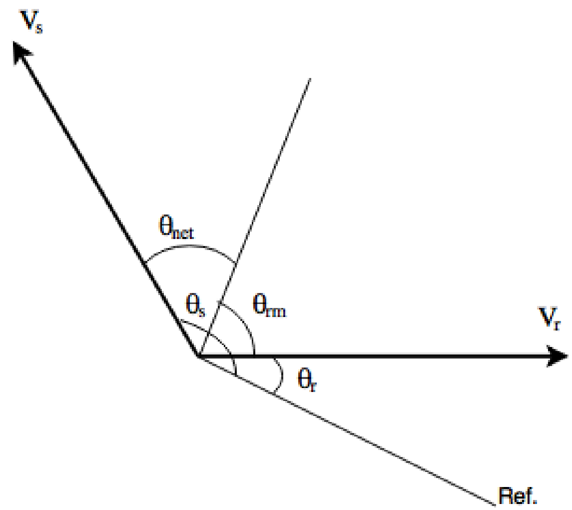

Figure 3.4: Phasor diagram representing the rotary transformer relationships (not scaled) [7]

For all power transmission systems there are a theoretical maximum power transmission capability. The maximum power which can be transmitted through the VFT is given by:

$$P_{VFTmax} = \frac{V_s V_r}{X_{sr}} \tag{3.2}$$

The maximum power transfer limit is reached if $\theta_{net} = \pm 90°$, where the polarity of θ indicates the direction of the power flow. As for any AC systems, a power angle of 90° also corresponds to the stability limit of the system. Hence, for a stable operation of the VFT, θ_{net} needs to be less than 90°. Resulting in a power transfer limited to a fraction of the theoretical maximum power transfer, P_{VFTmax}, given by Eq. 3.2. Within the range of the operating angles, θ_{net}, there are approximately a linear relationship between the power transfer and θ_{net}. This means that the power flowing through the VFT can be estimated by:

$$P_{VFT} \simeq P_{VFTmax} \theta_{net} \tag{3.3}$$

Where θ_{net} is given in radians.

3.3.2 Power Flow

In this section the active power balance and frequency shifting relationships in the VFT are described. The equations are based on an ideal rotary transformer, thus leakage reactance and magnetizing current are disregarded. In Fig. 3.3 the power flows through the VFT are presented in terms of generating mode and are positive. However, the power can flow in both directions depending on the operating mode. The power balance is given by:

$$P_s = P_D - P_r \tag{3.4}$$

The power balance indicates that the electrical power flowing out of the stator, P_s, must flow into the combined electrical path on the rotor, P_r, and the mechanical path to the drive system, P_D. As the VFT has similar operating conditions as a rotary transformer, there has to be a balance between the ampere-turns in the stator and rotor:

$$N_s I_s = -N_r I_r \tag{3.5}$$

Equation 3.5 can also be related to the magnetomotive force in the VFT by the relationship between the current flowing in the stator windings, I_s, and the current in the rotor windings, I_r. N_s and N_r is the number of windings in the stator and rotor, respectively. The magnetic flux link between the stator an rotor is the same, but the frequency varies. As a result of this, the voltage will differ with the same ratio as the frequency [9].

$$V_{sw} = N_s f_s \Psi_a \tag{3.6}$$

$$V_{rw} = N_r f_r \Psi_a \tag{3.7}$$

V_{sw} and V_{rw} are the voltages in stator windings and rotor windings, respectively, and f_s and f_r are the electrical frequencies given in hertz. Ψ_a is the air-gap flux linking the rotor and the stator by magnetic coupling. In steady state operation the rotor mechanical speed, f_{rm} is proportional to the difference in the electrical frequency on the stator and rotor windings.

$$f_{rm} = f_s - f_r \tag{3.8}$$

The rotor mechanical speed can also be found by means of the number of poles in the machine, N_P and f_{rm}:

$$\omega_{rm} = \frac{f_{rm}120}{N_P} \tag{3.9}$$

The slip of the VFT is obtained in the same way as for an induction machine. Here ω_s is the synchronous speed of the magnetic field given in rpm.

$$s = \frac{\omega_s - \omega_{rm}}{\omega_s} \tag{3.10}$$

By using the equations obtained so far (eq. 3.4 - 3.9) it is possible to express the power exchanged by the drive system:

$$\begin{aligned} P_D &= P_s + P_r \\ &= V_{sw}I_s - V_{rw}I_r \\ &= V_{sw}I_s - \left(N_r \frac{V_{sw}}{N_s}\frac{f_r}{f_s}\right)\left(N_s \frac{I_s}{N_r}\right) \\ &= V_{sw}I_s\left(1 - \frac{f_r}{f_s}\right) \\ &= P_s\left(1 - \frac{f_r}{f_s}\right) \end{aligned} \tag{3.11}$$

Now it is possible to obtain an expression for the torque produced by the DC motor, T_D:

$$\begin{aligned} T_D &= \frac{P_D}{f_{rm}} \\ &= V_{sw}I_s \frac{[(f_s - f_r)/f_s]}{(f_s - f_r)} \\ &= V_{sw}\frac{I_s}{f_s} \\ &= N_s f_s \Psi_a \frac{I_s}{f_s} \\ &= N_s I_s \Psi_a \end{aligned} \tag{3.12}$$

From Eq. 3.12 it can be observed that the motor drive torque, T_D, is independent of rotational speed. The torque is proportional to the stator current and air-gap flux. However, during normal operation the flux is nearly constant, thus the torque is only proportional to the stator current. If the frequency on the stator is constant, the power transfer through the machine is proportional to the applied torque [7]. Under no load conditions the torque, T_D, is zero, and at a load of one per unit, it is one per unit. When the two networks connected to the VFT operate at synchronous frequencies the power flow, with respect to applied torque, is linear.

The reactive power flow of a conventional ac circuit applies for the VFT. The difference in voltage magnitude of the two sides and the series impedance determines the reactive power flow through the machine. The aspect of reactive power flow will be explained in detail in chapter 4

3.4 Additional VFT Features

Power regulation is the normal mode of operation and the main control system of a VFT. Additionally, the automatic governor is implemented as a control function in the VFT to assist the interconnected networks during a large disturbance or fault. Power oscillation damping control is used to maintain system operation and stability during disturbances. Power runback is also a control alternative for the VFT. Furthermore are reactive power control systems required in a VFT, this topic is explained in detail in chapter 4. The different control systems are explained for the understanding of the VFT and its ability of control, however, the control systems will not be investigated further.

3.4.1 Power Regulation

The power regulation mode is related to the variable speed drive system and the DC-motor operation explained in section 3.2.3. The primary task of the control system is to maintain constant power transfer between the two interconnected networks. This is obtained by means of a rapidly responding closed loop power regulator [6]. Deviations in frequency will result in a change in rotational speed, and possibly the direction of rotation.

3.4.2 Governor

The automatic governor is one of the control functions which can be implemented in a VFT. It is used to adjust the power flow on a droop characteristic if the frequency exceeds a dead band [8]. The governor is operated to assist one of the networks during a large disturbance or fault leading to an imbalance in the generation or load. If the frequency falls below the dead band limit, the governor will respond by making the VFT increase power import, or decrease power export, to return the grid frequency to acceptable range [6]. The VFT is designed to operate with one side isolated [25]. This means that the VFT will continue to function if one side of the VFT becomes isolated, regardless of whether the isolated system has a local generation. In a situation with no local generation, the VFT will automatically provide all necessary power up to its full rating. If there is a local generation in the isolated system, the VFT will balance the distinction between generation and load, and share frequency governing with the local generator [8]

3.4.3 Power Oscillation Damping Control

In the case of an under-damped system only a minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency of the total electromechanical system [32]. Oscillation of machine angle will lead to power oscillations around the steady-state power transmitted. In some systems power oscillations may result in reduced power transmission capability. A disturbance in either side of the networks connected to the VFT might introduce power oscillations. Thus a power swing damping control is necessary to avoid the power swings affecting the system operation and stability. Power oscillations is a dynamic event and can be damped by a varying shunt compensation, which again will vary the voltage of the line, to counteract the accelerating and decelerating power swings. In a VFT the power oscillation damping control function adds damping to the inter-area electromechanical oscillations, typically in the range of 0.2 Hz - 1 Hz [25].

3.4.4 Power Runback

The Power Runback is a function which steps the power in a VFT to a fixed operational level [25]. A large disturbance in the network such as a line outage or loss of a generator will trigger the runback function. A 100 MW VFT can run at a power level between $\pm$ 100 MW. If a critical line is lost, a considerable amount of power rejection can be provided by the VFTs power runback system. Normally the VFT control system is designed to provide up to four runbacks with independent triggers and runback levels [6].

3.5 Compatibility with Nearby Grid Components

One of the main advantages of the VFT is its ability to collaborate with nearby grid components. The VFT has proven to be an advantageous addition to the network compared to other power electronic devices which are a cause of considerable amounts of concerns. The VFT is a viable interconnection technology for the existing grid, and also for the smart grid of the future [11].
As the VFT share many of the same components as the hydro-generator, including the stator itself, the machine works well together with electrical generation units. Electrical generators can be classified as large rotating machines with significant inertia. The VFT is also a large rotating machine with a considerable amount of inertia, allowing the VFT to ride through grid disturbances smoothly [29]. Although electrical generators such as steam turbines and combustion turbines have a much higher rotational speed than the normal operating speed of the VFT, the physical similarities make the VFT naturally compatible. The large inertia of the VFT induces smooth and analog changes to the power order which is preferred rather than fast, stepwise or discrete. When a VFT is connected to the network both system damping and stability is significantly improved [11].

During a line fault and trip event, the VFT is able to supply active power immediately after the fault, which decreases the lines transient reactive power absorption substantially. The significant reduction in reactive losses frees the reactive power needed to restore the voltage level in the system [33]. The VFT is a bi-directional transmission device, thus power can flow in both directions through the machine. If reactive power is needed in one side of the VFT as a consequence of a fault, the VFT can provide the necessary reactive power from the other side. The VFT is an induction machine which absorbs reactive power, thus additional reactive power compensation is required. The matter of reactive power compensation will be further investigated in chapter 4 and 5.

3.6 Model Topology/ Simulation setup

The dynamic performance of a VFT is analyzed using MATLAB/Simulink. The aim of the analysis is to provide an understanding of the basic principles of operation of the VFT in terms of power flow direction and magnitude. A single line diagram of the system is presented in fig. 3.5. The VFT is based on the Simulink doubly fed asynchronous machine, constructed with a wound rotor. In this study, the machine is used as an interconnection between two grids represented by two ideal sources, each with operating frequency of 60 Hz. On each grid side, a resistive load of 20 MW is connected. The DC-motor and variable speed drive system is simplified to a power order step signal. This means that the torque is set manually to the desired amount of active power exchange between the two networks.The following assumptions have been considered:

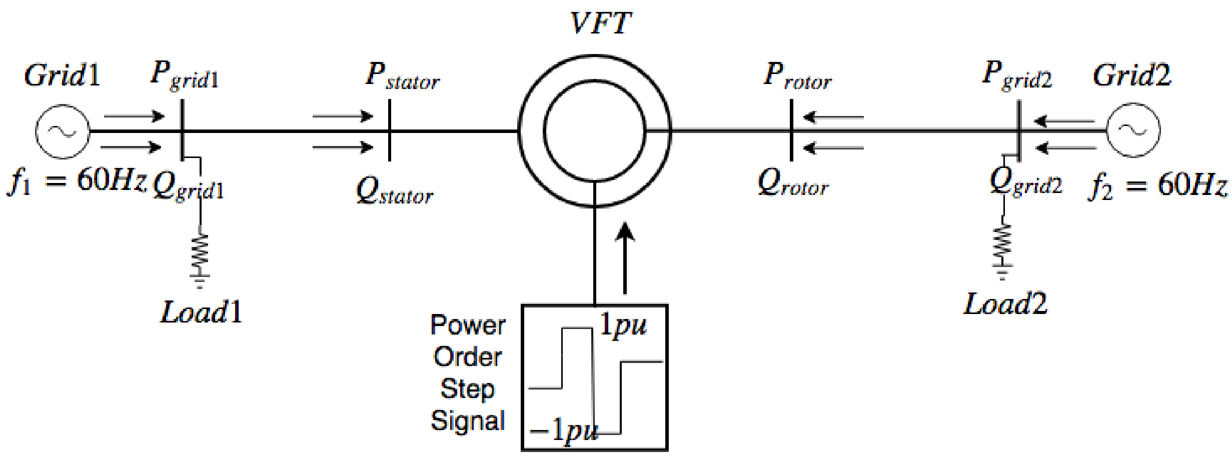

Figure 3.5: Single Line Diagram of the System

Assumptions:

- The convention of power flow used in every simulation case is the same as shown in fig. 3.5.
- Positive polarity indicates power flowing towards the VFT.
- Negative polarity indicates power flowing away from the VFT.
- Powers flowing to/from grid 1 is further referred to as power in grid 1, P_{grid1}, Q_{grid1}.
- Powers flowing through the stator windings of the VFT will be addressed as power in the stator, P_{stator}, Q_{stator}.
- Powers flowing through the rotor windings of the VFT will be addressed as power in the rotor, P_{rotor}, Q_{rotor}.
- Powers flowing to/from grid 2 is further referred to as power in grid 2, P_{grid2}, Q_{grid2}.
- The MATLAB/Simulink model shown in fig. 3.6 is used as basis for all case studies utilized in this thesis.
- Machine parameters are listed in Table 3.1, and system parameters can be found in Table 3.2.
- The 100 MW VFT electrical machine parameters are obtained from [6], with a few modifications to acquire a smother simulation.
- Torque is applied to the rotor shaft as a power order step signal.

Table 3.1: Machine Parameters

VFT Parameters	Symbol	Value	Unit
Nominal Power	P_{nom}	100	MW
MVA_{base}	S_{base}	100	MW
Pole pairs	p_p	4	
Inertia	H	25	pu-sec
Friction Factor	D_{pu}	0.01	pu
Stator Reactance	X_s	0.006	pu
Rotor Reactance	X_r	0.006	pu
Magnetizing Reactance	X_m	5	pu
Stator Resistance	R_s	0.01	pu
Rotor Resistance	R_r	0.01	pu
Stator Inductance	L_s	0.006	pu
Rotor Inductance	L_r	0.006	pu
Magnetizing Inductance	L_m	5	pu

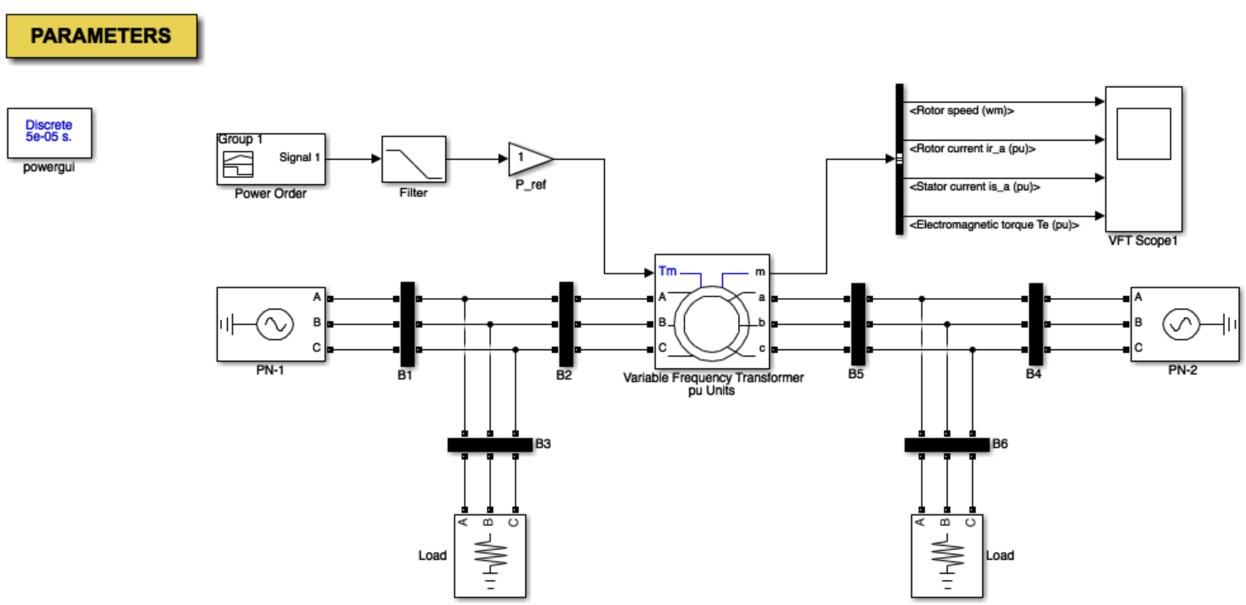

Figure 3.6: The MATLAB/Simulink model of the base case system

Table 3.2: System Parameters

System Parameters	Symbol	Value	Unit
AC Voltage Grid 1	V_1	17	kV
AC Voltage Grid 2	V_2	17	kV
Frequency grid 1	f_1	60	Hz
Frequency grid 2	f_2	60	Hz
Power Rating Load 1	P_{Load1}	20	MW
Power Rating Load 2	P_{Load2}	20	MW

3.7 Simulation Results

3.7.1 Case 1: Base Case

The base case is a simulation study of the system explained in the model topology, section 3.6, comprising of two strong grids interconnected by a VFT. Both networks are represented by ideal sources operating at 60 Hz. The power flows, torque and slip of the machine will be presented and evaluated in this section.

Objectives:

- Provide a basic understanding of the performance of a VFT used as an interconnection between two synchronous AC grids by means of a simulation study.
- Evaluate active and reactive power flows in the system, in terms of direction and magnitude.
- Evaluate the step response of the VFT, including active power and power angle.

Observations:

- Magnitude and direction of active power is determined by the power order signal applied to the rotor. The polarity of the power order signal determines the direction of power flows.
- A certain amount of uncontrolled reactive power will flow in the system.
- The VFT will consume some reactive power in order to build up the magnetic flux fields.

The DC drive motor is connected to the shaft of the rotor in the VFT, and its main task is to apply torque to the rotor shaft to adjust the position of the rotor. The DC motor torque is modeled in MATLAB/Simulink as a power order signal which applies a step signal to the rotor shaft. The step signal procedure is as follows:

Procedure:

- 0 - 50 sec. Power order signal is zero, hence no active power flow.
- 50 - 70 sec. Power order signal steps up to 1 pu. Active power is transmitted between the two power systems through the VFT.
- 70 - 90 sec. Power order signal steps down to -1 pu. Direction of active power flow reverses.
- 90 - 150 sec. Power order signal equals 0.5 pu. Direction of active power flow reverses and power magnitude is halved.

Figure 3.7 and 3.8 illustrates how the VFT responds to steps in power order. The red curve shows the torque applied to the rotor stepping from 0 to 1 pu (100 MW), to -1 pu and up to 0.5 pu. For positive values of power order signal/torque, the active power flows from stator side to rotor side, and for negative power order signals, the direction of power flow reverses, hence flowing from rotor side to stator side. The blue trace in figures 3.7 and 3.8 displays the VFT actual power transfer and the angle of the VFT rotary transformer. According to theory, the direction of the active power flow through the VFT is depending on the polarity of the applied torque. From eq. 4.5 it is justified that applied torque from the DC drive motor is proportional to active power in the stator side. This can be observed in fig. 3.7, as the blue curve follows the applied power signal (red curve). In the base case, the two interconnected grids operate at equal frequency. Thus for the VFT to be able to transfer power between the two systems the rotor angle has to adjust itself to follow the phase angle difference between the two grids, this operation is observed in fig. 3.8.

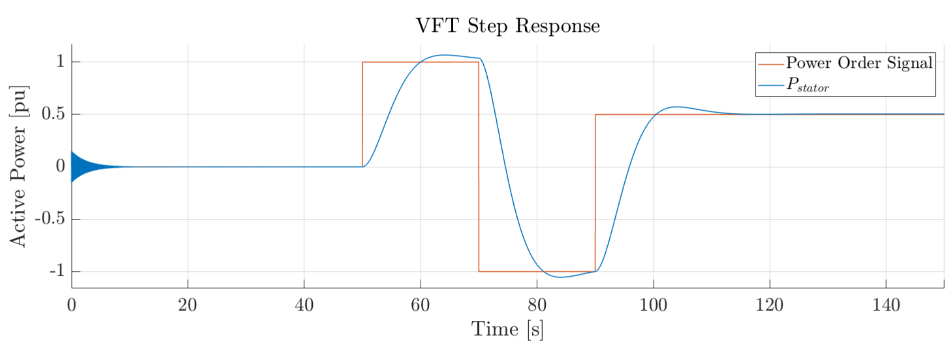

Figure 3.7: VFT Step Response

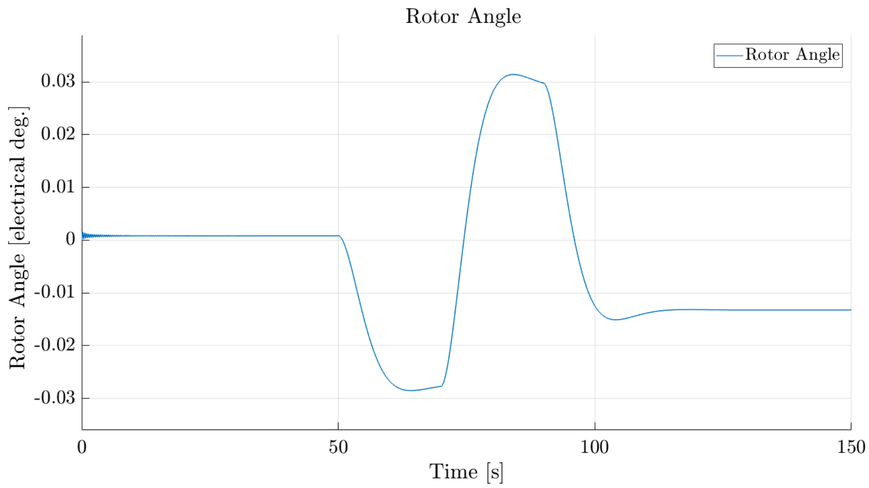

Figure 3.8: VFT Rotor Angle

The active power flowing through the machine is affected by the slip. This can be justified by eq. 2.20. For the base case, it is observed in fig. 3.9 the slip equals 1, hence the rotational speed of the machine is stall (stand still). According to eq. 2.17 a unity slip implies that $|P_s| = |P_r|$, which is confirmed by the curves in fig. 3.10 and 3.11 being equal, only reflected due to the convention of power flow. By eq. 2.3 a unity slip is expected as the frequency difference between the two interconnected power systems is 0 Hz.

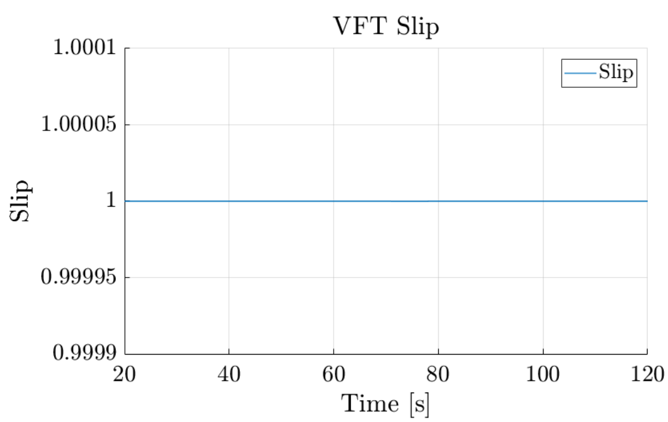

Figure 3.9: Slip of the VFT.

The power order applied to the rotor shaft defines the amount of power to be transferred through the VFT. Figure 3.10 and fig. 3.11 represents the active power in the stator and the rotor, respectively. As previously explained, the stator power flow is regulated by the torque applied to the rotor shaft.

The curve presenting the rotor power is the inverse of the stator power, this is due to the convention of power flows determined in the MATLAB/Simulink model, where positive powers are flowing into the VFT. Approximately all active power is transmitted through the VFT. However, in a more realistic case, as eq. 3.11 states, some power might flow in the DC drive motor system to regulate the rotational speed of the machine. In this simulation model, the DC drive motor is represented by a power order signal, which does not require power to function.

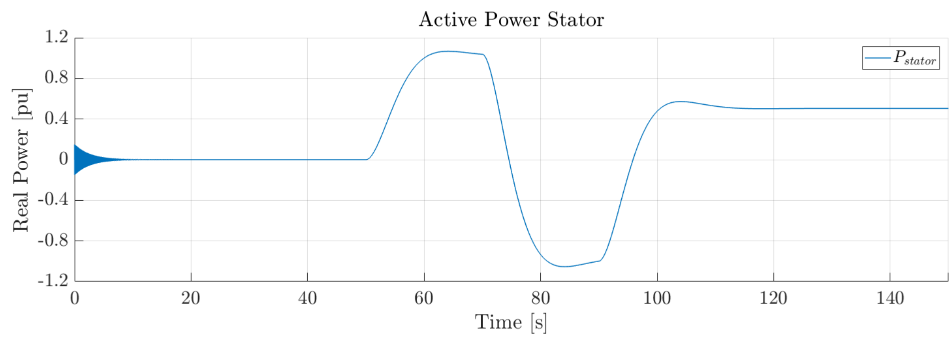

Figure 3.10: Power flow through Stator

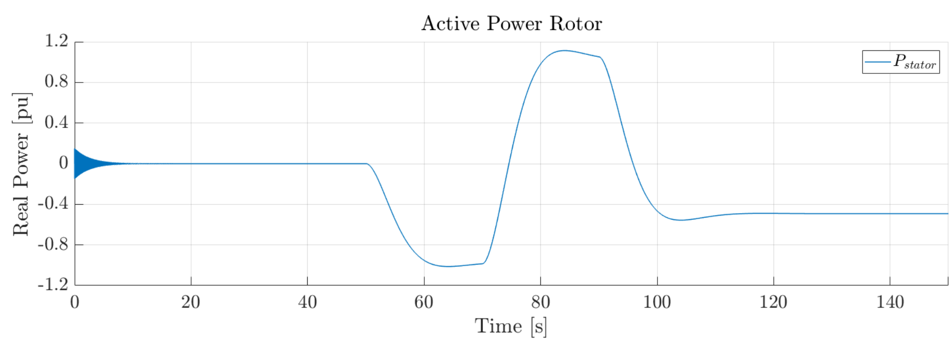

Figure 3.11: Power flow through Rotor

The two figures 3.12 and 3.13 represents the reactive power flow in the stator and rotor respectively. During the first time period, from 0 to 50 seconds, when the torque and active power flow is zero, it is observed a reactive power flow into the VFT approximately equal 0.15 pu from each side. During the first power step, when 1 pu active power is flowing from stator side to rotor side, approximately 1.9 pu of reactive power is flowing in the opposite direction. The power order signal steps down to -1 pu at 70 seconds and the direction of both active and reactive power flow is reversed. Now 1.9 pu of reactive power flows from grid 1 through the VFT towards grid 2. During the step response from 50 seconds to 150 seconds, it can be observed a difference in the magnitude of reactive power flowing into the machine compared to the amount flowing out. At approximately 65 seconds the reactive power flowing into the rotor windings is close to 1.9 pu, while the amount flowing out of the stator windings is only 1.6 pu. This is explained by the fact that the VFT consumes a certain amount of reactive power as long as it is energized. Similar to the conventional induction machine the VFT requires reactive power to obtain flux fields needed for active power transfer. This is also observed in the period from 0 to 50 second as 0.15 pu reactive power is flowing from both grids to the VFT. The machine consumes reactive power even though no active power is flowing. The reactive power which is not absorbed by the VFT, but just passes through, is denoted as uncontrolled or undesired reactive power. One reason for the uncontrollable reactive power exchange through the machine may be a response to the change in magnitude and direction of the active power. This undesirable reactive power flow contributes to reduced active power handling capability of the VFT. In the base case no reactive power compensation is implemented, thus the reactive power requirement of the VFT and the uncontrolled reactive power exchange must be supplied by the two grids in each side. An alternative solution to this problem is to implement reactive power compensation at the two grid sides. The reactive power issue will be further investigated in chapter 4.

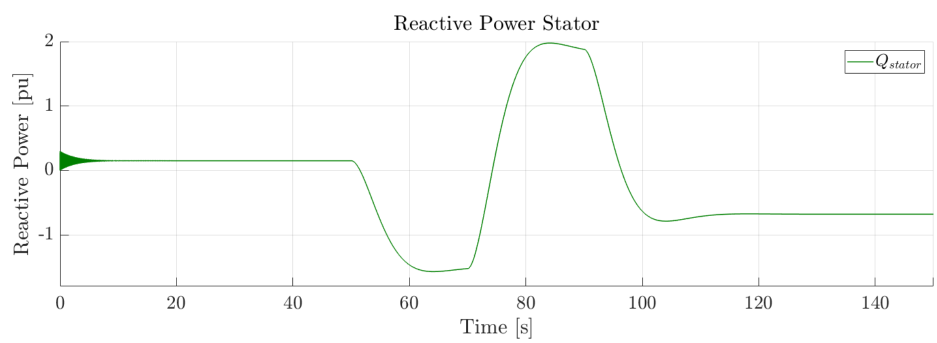

Figure 3.12: Reactive power flow on stator side.

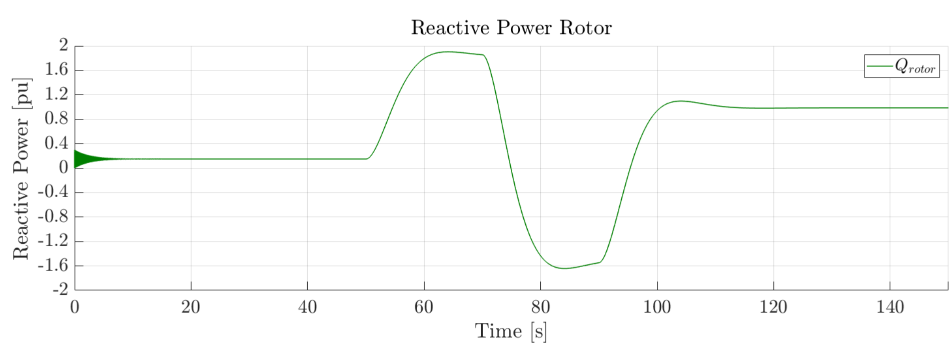

Figure 3.13: Reactive power flow on rotor side.

Figure 3.14 illustrates the difference between the magnitude of reactive power flowing into the machine and the magnitude flowing out. This amount of reactive power is consumed by the stator and rotor leakage reactance and the magnetizing reactance of the VFT. The difference in magnitude of reactive power in stator and rotor is approximately 0.3 pu during the whole simulation period. When the power order signal changes magnitude and direction, from 0 to 1 pu, further decreasing to -1 pu before it rises to 0.5 pu, it is observed that the reactive power requirement of the VFT experience a slight increase, observed as two pulses in the figure. When the direction and magnitude of the power order change, torque must be applied to the rotor shaft in order to adjust the rotor position relative to the stator. Thereby, controlling the magnitude and direction of the active power exchange through the VFT. The torque applied will influence the magnetic fields of the machine, and the magnetic fields will require a higher amount of magnetizing current to obtain a new alignment. During this alignment phase the VFT consumes a higher amount of reactive power, as observed in fig. 3.14. When the active power exchange reaches steady state operation supplying gird 2 with 0.5 pu of active power, the reactive power consumed by the VFT is approximately 0.31 pu, which corresponds to 31 MVar.

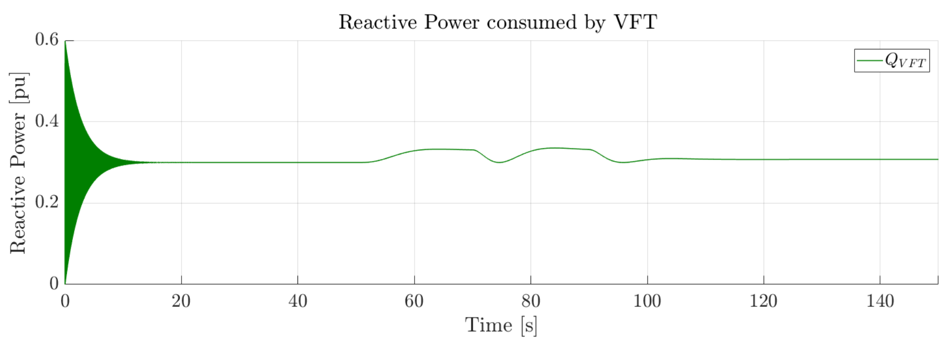

Figure 3.14: Reactive power consumed by the VFT

3.8 Summary

The Variable Frequency Transformer is presented as a novel frequency converter to control bidirectional power flows between asynchronous systems. The mechanical design is based on the conventional rotary transformer. Power is being transmitted through the air-gap between the rotor and stator by the principle of induction. The operation of the VFT is similar to the phase shifting transformer. By means of a DC motor and a variable speed drive system torque is applied to the rotor shaft to regulate rotor position with respect to the stator, thus adjusting the phase angle. Due to the adjustable phase angle magnitude and direction of power can be controlled. Simulation result of a simple study case of the VFT provides an understanding of the basic operation of the machine. The simulation results show that the power flowing through the VFT can be controlled by applied torque and that reactive power will be present during the operation.

Chapter 4

Reactive Power Requirements of a VFT

In conventional power systems the flow of reactive power depends on the difference in the per unit voltage of the two points, and the series impedance between the two points [34]. A power system which experience a shortage in reactive power may exhibit a low voltage condition. A power system exposed to too much reactive power can cause voltages to become too high, or even unstable. Thus a balance of reactive power is important to keep the system stable. With the increased implementation of variable RES in the power systems follows challenges related to unbalance in production and demand of energy affecting voltage stability and frequency, additionally reducing the Short Circuit Ratio (SCR) of the network. The VFT has proven to be a viable alternative for interconnecting weaker grids to the distribution network [3] as it provides system flexibility and independent control of active power. A VFT is based on the principle of induction and consequently consuming reactive power [15]. By means of capacitor banks the reactive power requirement of the VFT can be covered.

This chapter looks further into the reactive power requirement of the VFT. A study of the performance of the VFT in a weaker grid interconnection is obtained and analyzed by means of a simple MATLAB/Simulink model. The same model is used for investigating the impact of capacitor banks combined with the VFT system.

4.1 Reactive Power Requirements of a VFT

The operation of a VFT requires reactive power due to magnetizing currents flowing in the windings which generates rotating fields [35]. The VFT is based on the principle of induction, hence power is being exchanged by magnetic coupling in the air-gap. For the VFT to be able to transfer power between the two networks it is dependent on the stator and rotor rotating magnetic fields. Reactive power, due to reactive magnetizing currents, is needed for producing rotating magnetic field in the machine. The reactive power is provided by the grid, or by external capacitor banks [11]. Also, depending on the VFT operating conditions, uncontrollable reactive power can flow between the two power networks through the VFT. The reactive power flow through the VFT is similar to the flow of reactive power in a power system. The flow of reactive power is determined by the voltage difference between two points in the network, and by the series impedance between those two points [36]. This holds true even for a VFT connecting two asynchronous systems. The VFT allows for reactive power to flow through the machine in order to support either side if needed. This is the natural response, i.e. the passive response of the machine, and not a result of a tuned system [37].

A challenge regarding the VFTs absorption of reactive power is that the amount of required reactive power may be unequally distributed on the two sides. The reactive power distribution is dependent on the operating conditions of the VFT. Additionally, uncontrollable reactive power exchange between the two networks might occur, forcing to reduce the effective active power transfer to avoid over currents in the machine [38]. The reactive power consumption of a VFT increases with the size of the machine [3]. Although the effective reactance decreases when the size of the VFT increases, the reactive power requirement increase due to increased power flowing through the VFT reactance.

4.2 Steady State Reactive Power

As mentioned, the reactive power flow through the VFT is determined by the difference in voltage magnitude on the two sides and the impedance of the rotary transformer. The reactive power can be provided by both grids connected to the VFT, depending on the phase angle of the voltages on each side. A simplified single-phase equivalent circuit of a typical WRIM referred to the stator side, shown in fig. 4.1, is considered in order to obtain the reactive power flow equations in the VFT [15]. Whereas, v, i, R, L, Z and s represents the voltage, current, resistance, inductance, impedance and slip respectively. The subscripts s and r refers to the stator side and rotor side respectively. Rotor parameters referred to the stator side are denoted with the subscript '. By means of the superposition principle the instantaneous stator and rotor circuit currents are obtained from the single-phase equivalent circuit in fig. 4.1 [38].

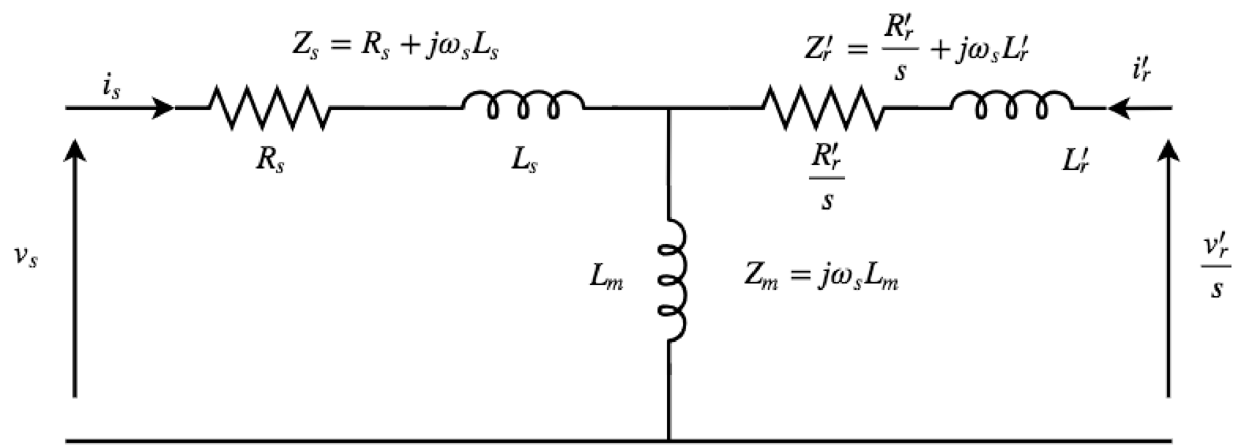

Figure 4.1: Wound Rotor Induction Machine steady-state equivalent circuit

$$i_s = v_s\left(Z_s + \frac{Z_m Z_r'}{Z_m + Z_r'}\right) - \frac{v_r'}{s}\left(Z_r' + \frac{Z_m Z_s}{Z_m + Z_s}\right)\left(\frac{Z_m}{Z_m + Z_s}\right) \tag{4.1}$$

$$i_r' = \frac{v_r'}{s}\left(Z_r' + \frac{Z_m Z_s}{Z_m + Z_s}\right) - v_s\left(Z_s + \frac{Z_m Z_r'}{Z_m + Z_r'}\right)\left(\frac{Z_m}{Z_m + Z_r'}\right) \tag{4.2}$$

The rotor resistance can be divided in two parts:

$$\frac{R_r'}{s} = R_r' + R_r'\left(\frac{1-s}{s}\right) \tag{4.3}$$

The same can be done with the rotor voltage:

$$\frac{v_r'}{s} = v_r' + v_r'\left(\frac{1-s}{s}\right) \tag{4.4}$$

From this the WRIM equivalent circuit is modified to the equivalent circuit of the VFT presented in fig. 4.2, including the DC-drive motor. Based on the VFT equivalent circuit the real and reactive powers at the stator side and rotor side is obtained:

$$P_s = Re(v_s i_s^*) + P_{DC} \tag{4.5}$$

$$P_r = Re(v_r' i_r'^*) \tag{4.6}$$

$$Q_s = Im(v_s i_s^*) \tag{4.7}$$

$$Q_r = Im(v_r' i_r'^*) \tag{4.8}$$

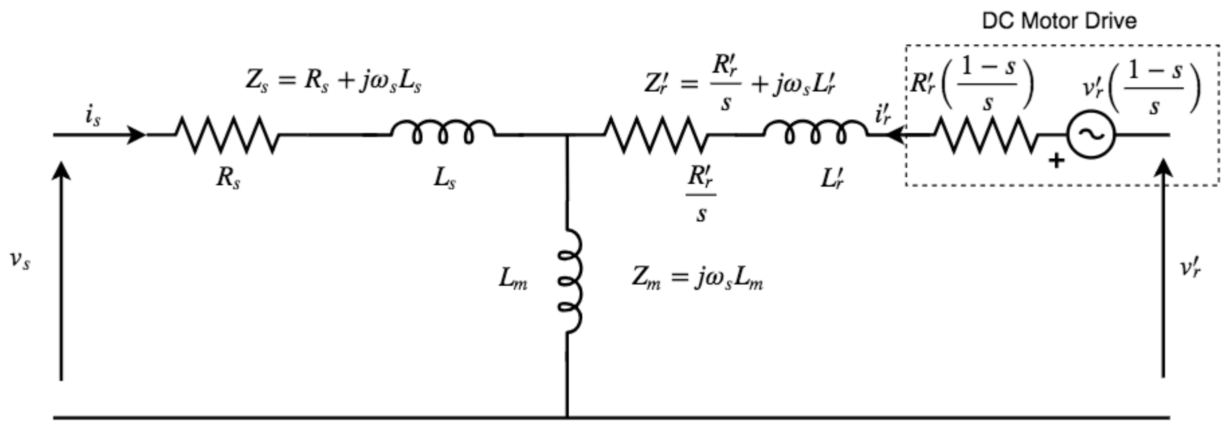

Figure 4.2: VFT Steady-state equivalent circuit [38]

Where P_s is defined as the real power in the stator side and P_r is the real power in the rotor side. Q_s and Q_r is the reactive power in stator and rotor side, respectively. As the DC motor drive is electrically coupled to the stator side of the VFT, the real power on the stator side, eq. 4.5, is the sum of the real power in the stator circuit ($Re(v_s i_s^*)$) and the power in the DC drive motor P_{DC}. P_{DC} can be computed as [38]:

$$P_{DC} = Re\left[v_r' i_r' \left(\frac{1-s}{s}\right)\right] - |i_r'|^2 R_r' \left(\frac{1-s}{s}\right) \tag{4.9}$$

The convention of power flow directions is as presented in fig. 3.3. The effective reactive power requirement of the VFT, Q_{tot} is given by [9]:

$$Q_{tot} = Q_s + Q_r \tag{4.10}$$

Moreover, Q_{tot} can also be expressed the effective reactive power consumed by the magnetizing reactance, Q_m and the combined reactive power consumed by the rotor and stator leakage reactance, Q_l [24].

$$Q_{tot} = Q_m + Q_l \tag{4.11}$$

The reactive power can be provided by both networks connected to the VFT, and the amount is dependent on the phase angles of the voltages on each side of the machine.

4.3 Reactive Power and Voltage Stability

According to IEEE's definition of Power System Stability, voltage stability refers to the electrical power systems ability to keep all bus voltages at steady state during normal operating conditions, and after being exposed for a disturbance in the system [34]. Inability to satisfy the reactive power demand is the main factor causing voltage instability [39]. A system is voltage unstable if the voltage magnitude at one bus decreases as reactive power is injected to the same bus [34]. Control of reactive power is in some cases the solution to improved power quality and voltage stability.

4.3.1 Weak grid

A grid can be characterized by different parameters, such as voltage level and its total power capability. Additionally the Short Circuit Capacity (SCC) can be defined for a network. The SCC is the amount of power flowing at a given point in case of a short circuit. A grid is considered as weak if the SCC of the grid is low [1]. The Thevenin equivalent of the network can be used to analyze the SCC of a system, where the rated voltage E_{ac} and the absolute value of grid impedance Z_{grid} are the important parameters [1]. The grid impedance is the sum of the impedances of many grid components and will vary from grid to grid. The AC system can be considered as ”weak” from two aspects [34]:

i. AC system impedance may be high

ii. AC system mechanical inertia may be low

Since the strength of the AC system will have a significant impact in the system interactions it is useful to have a simple measure of the strength of the system. The SCR has developed as such a measure, and can be used for comparing the strength of different AC systems. If an active load such as the VFT is connected to an AC system the SCR is defined as [34]:

$$SCR = \frac{Short-Circuit MVA of AC system}{VFT MW rating} \frac{SCC}{S_{N,VFT}} = \frac{U_{grid}^2}{Z_{grid} S_{N,VFT}} \tag{4.12}$$

where the short circuit MVA is given by:

$$SC_{MVA} = \frac{U_{grid}^2}{Z_{grid}} \tag{4.13}$$

Another parameter of importance when analyzing the strength of the grid is the X/R-ratio. The X/R-ratio is the rate between the reactive and ohmic parts of the grid impedance Z_{grid}. Weak grids typically have a low X/R-ratio, approximately 0.5 [40]. When power is being fed into a network the fault level is an important characterization. The fault level is also known as the short circuit level. The fault level at the Point of Common Coupling (PCC) determines the effect the generator/power injection will have on the strength of the grid. A weak grid is a network with a low fault level, which means a network with a high grid impedance [1]. On the other hand, changes in voltage magnitude could lead to large variation in reactive power. According to the European standard EN 50160, the transmission network might be exposed to deviations in voltage levels within specified tolerance range of $\pm 10\%$ [41]. A weak grid connection is a source of such voltage variations, and reactive power flows at this point might become critical with respect to voltage collapse. Weak grids has a very small reactive power margin compared to strong networks, and during weak grid conditions the voltage is extra sensitive to change in reactive power support [42]. Thus, reactive power support is necessary to improve system performance, and adjust the voltage unbalance.

4.4 Simulations

4.4.1 Case 2: Reactive power requirement of the VFT

In case 2 the reactive power requirement of the VFT system will be addressed. In the base case it was noticed a relatively large amount of reactive power flowing in the system in addition to the amount of reactive power consumed by the VFT. The aim of case 2 is to investigate the relationship of active and reactive powers flowing in the system in terms of magnitude and direction. The VFT response to a weaker grid interconnection will also be investigated.

Objectives:

- Determine reactive power requirements of the VFT system when different magnitudes of active power is transferred through the machine.
- Investigate the amount of reactive power absorbed in the VFT.
- Examine the response of the VFT in terms of reactive power flow when a weaker grid is connected to one side of the machine.

Observations:

- By observations made in the base case it is assumed that reactive power will flow in the opposite direction of active power flow.
- VFT will consume reactive power due to magnetizing and leakage reactance. Thus, reactive power will flow even though active power transmission is zero.
- The difference in magnitude between the reactive power flowing into the VFT and the reactive power flowing out of the VFT equals the amount of reactive power absorbed by the machine.
- Magnitude of reactive power will increase/decrease according to the magnitude of active power flow.

In the following the reactive power requirement of the VFT system is evaluated in two ways:

Scenarios:

1. For various amounts of active power flow through the machine.
2. For various amounts of active power flow through the machine when one grid is weaker (not ideal source).

Scenario 1. Reactive power characteristic of the VFT for different magnitudes of active power flow

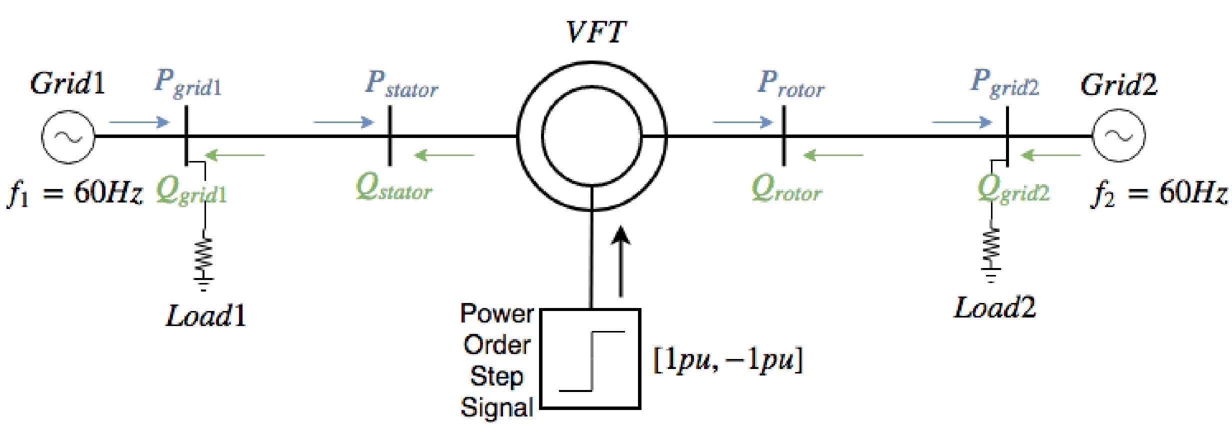

Figure 4.3: Single Line Diagram of the VFT system analyzed in Case 2 Scenario 1

The model topology used for the analysis of reactive power in the VFT is presented in fig. 4.3. The VFT interconnects two strong grids, both operating at a frequency of 60 Hz. The grid side voltages are maintained at their nominal values, $|v_s| = 1pu$ and $|v_r| = 1pu$. To determine the reactive power needed in the system to transfer different amounts of active power, a steady state analysis is performed.

Procedure:

- Power order applied as a single step starting at 0 and increasing to 1 pu at 50 seconds.
- Register the steady state active and reactive power flows.
- Run a new simulation with a power order step signal increasing from 0 to 0.8 pu at 50 seconds.
- For each simulation the power order step decreases with 0.2 pu until -1 pu.

Table 4.1: Power flows in pu for different amounts of applied torque

Power order	Q_{stator}	Q_{rotor}	Q_{VFT}	P_{stator}	P_{rotor}	P_{VFT}
1	-1.5	1.83	0.3299	1.022	-0.9714	0.05058
0.8	-1.172	1.491	0.3191	0.8136	-0.7811	0.03247
0.6	-0.8436	1.154	0.3107	0.6072	-0.5888	0.0184
0.4	-0.5136	0.8183	0.3046	0.4028	-0.3945	0.00834
0.2	-0.1825	0.4835	0.301	0.2005	-0.1982	0.0023
0	0.1499	0.1499	0.2998	0.00015	0.00015	0.0003
-0.2	0.4835	-0.1825	0.301	-0.1982	0.2005	0.0023
-0.4	0.8183	-0.5136	0.3046	-0.3945	0.4028	0.00834
-0.6	1.154	-0.8436	0.3107	-0.5888	0.6072	0.0184
-0.8	1.491	-1.172	0.3191	-0.7811	0.8136	0.03247
-1	1.83	-1.5	0.3299	-0.9714	1.022	0.05058

The power order and the corresponding power flows in the VFT system is listed in Table 4.1. The effect of active power transfer control on the reactive power flow through the VFT is illustrated by the red curve in fig. 4.4, showing the reactive power characteristics curve of the VFT. The dashed line is the reactive power in the rotor windings, and the solid line is the reactive power in the stator windings. Power flows with positive polarity flows into the VFT and power flows with negative value flows out of the machine. Figure 4.5 illustrates reactive power consumed by the VFT for different amounts of active power flow. It is observed that active and reactive power flows operate at different polarity, hence flows in opposite direction, except in the case where power order is zero. For this situation approximately no active power flows in the machine, and all reactive power, 0.3 pu, goes to the magnetizing reactance of the VFT. For the situation of zero power order it is also observed that an equal amount of reactive power is supplied by both grids. In this mode of operation there is no net transfer of reactive power through the VFT, and both the rotor and stator contribute equally to magnetization of the machine.

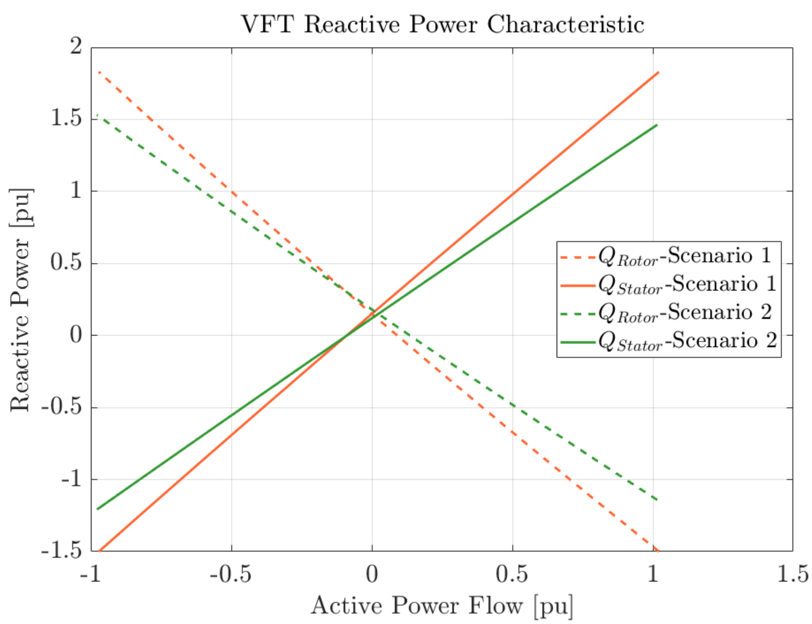

Figure 4.4: VFT reactive power characteristic under varying magnitudes of active power transfer. Red curve is scenario 1 and green curve is scenario 2. Dashed lines represents power in the rotor windings and the solid lines represents power in the stator windings.

As observed in fig. 4.5 the consumed reactive power increases with magnitude of active power. In fig. 4.4 it can be observed that the total reactive power in the system increase linearly with active power transfer. Despite no deviation in grid side voltages, the amount of uncontrolled reactive power exchange is large.

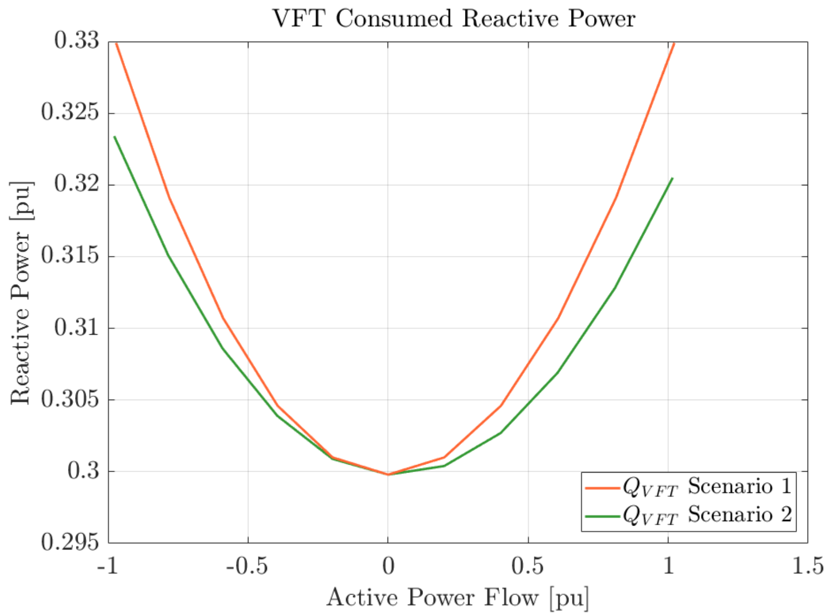

Figure 4.5: Reactive power consumed by the VFT. Red curve is scenario 1 and green curve is scenario 2.

When the active power flow has a maximum value of 1.022 pu, equivalent to 102.2 MW, the uncontrolled reactive power exchange is 1.5 pu, which equals 150 MVar. Simultaneously, the reactive power consumed by the VFT reaches the highest amount with a value of 0.3299 p.u, corresponding to 32.99 MVar, as observed by the red curve in fig. 4.5.

The reactive power consumed by the VFT increases as the amount of active power transfer increases in either direction. One explanation to this can be found in the steady state equivalent circuit of the VFT, shown in fig. 4.2. When power flows in the machine, current will flow in the impedances of the machine Z_s, Z_r' and Z_m. A greater part of the current will choose the path with least impedance, hence, through the stator and rotor. However, some current will flow in the magnetizing branch and through the inductance, L_m. In a conventional transformer the inductance is much higher than the inductance in a VFT, hence the reactive power consumption is higher for the VFT compared to the transformer. The current in the magnetizing branch is the current which set up and sustain the magnetic fields required for power transfer. As the power injected to the machine increases, a higher current will flow in the magnetizing branch. This is one explanation to the increased reactive power consummation of the VFT when active power increase.

Scenario 2. Reactive power characteristic of the VFT for different magnitudes of active power flow when connected to a weaker grid

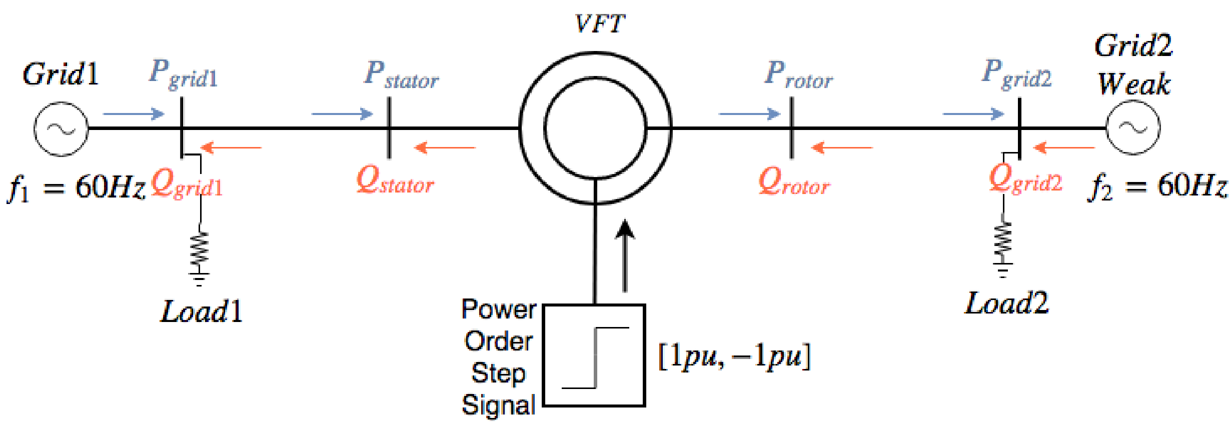

Figure 4.6: Single Line Diagram of the VFT system analyzed in Case 2 Scenario 2.

So far the VFT have been analyzed as an interconnection between two strong grids, modeled by ideal sources. A more realistic approach is to have non-ideal sources connected to the VFT, representing weaker grids, meaning grids with lower short circuit ratio where voltage magnitude might vary. As previously explained voltage and reactive power are strongly dependent on each other, and both parameters have a significant impact on the system stability. In the following analysis, the base case model is modified by a weaker grid connection at the rotor side, see fig. 4.6. The system at stator side is unchanged and still modeled by an ideal source, hence voltage in this side will maintain at 1 pu. The weaker grid connection is obtained by specifying the short circuit parameters of the source. A three-phase short circuit level of 50 GVA and a X/R-ratio of 15 is chosen as suitable parameters. For this case, the grids are operating at a synchronous frequency equal 60 Hz. The torque applied to the rotor will be a step signal stepping from 0 to 1 pu at 50 seconds. The polarity of the applied signal is positive, hence grid 1 supplies grid 2 (the weaker grid) with active power.

Procedure:

- Power order applied as a single step starting at 0 and increasing to 1 pu at 50 seconds.
- Register the steady state active and reactive power flows.
- Run a new simulation with a power order step signal increasing from 0 to 0.8 pu at 50 seconds.
- For each simulation the power order step decreases with 0.2 pu until -1 pu.

Table 4.2: Power Flows in pu with a weaker grid connection at rotor side

Power order	V_2	Q_{stator}	Q_{rotor}	Q_{VFT}	P_{stator}	P_{rotor}	P_{VFT}
1	0.9971	-1.142	1.463	0.3205	1.016	-0.9792	0.03636
0.8	0.9976	-0.8801	1.193	0.3128	0.8095	-0.7863	0.02321
0.6	0.9982	-0.6166	0.9235	0.3069	0.605	-0.592	0.013
0.4	0.9987	-0.352	0.6547	0.3027	0.4018	-0.3961	0.0058
0.2	0.9992	-0.0862	0.3866	0.3004	0.2003	-0.1987	0.00158
0	0.9998	0.1806	0.1192	0.2998	0.0002	0.000066	0.0003
-0.2	1	0.4486	-0.1477	0.3009	-0.1984	0.2004	0.00202
-0.4	1.001	0.7177	-0.4138	0.3039	-0.3955	0.4022	0.0067
-0.6	1.001	0.9879	-0.6793	0.3086	-0.5912	0.6055	0.0143
-0.8	1.002	1.259	-0.9441	0.3151	-0.7853	0.8103	0.02496
-1	1.002	1.532	-1.208	0.3234	-0.978	1.017	0.03856

Reactive power flows corresponding to scenario 2 is represented by the green curves in fig. 4.4 and 4.5. Fig. 4.4 presents the reactive power flowing through the VFT for different magnitudes of active power flows when a weaker grid is connected to the rotor side. The solid line represents the reactive power flowing in the stator windings, while the dashed line represents the reactive power in the rotor windings. The green curve in fig. 4.5 illustrates the amount of absorbed reactive power by the VFT. The steady state power flows are also presented in Table 4.2. Similar to scenario 1, the active and reactive power flows through the VFT in an adverse direction. When P_{stator} is positive Q_{rotor} is negative, and opposite. In comparison to scenario 1, the reactive power trends are the same, implying that reactive power increases as active power increase. However, the total reactive power in the system is lower compared to scenario 1. The highest reactive power flow occurs when the active power transfer is highest. This is the situation with a power order of 1 pu, then the uncontrolled reactive power is approximately 1.1 pu. At zero power order both stator and rotor reactive power is positive, hence both sides provide the VFT with reactive power. Unlike scenario 1, the magnitudes are not equal as the stator side provides a higher amount of reactive power compared to the rotor side, 0.1806 pu and 0.1192 pu respectively. This can be explained by the fact that the short circuit level of grid 2 is lower in scenario 2 compared to scenario 1. Hence, for this scenario, the voltage at the grid connection might fluctuate and affect the reactive power. It can be observed in Table 4.2 that the voltages, V_2, changes with the power order. Reactive power and voltage are parameters which affect each other, as explained in detail in section 4.3.1. When the power order reaches a value of 1 pu, the voltage drops by 0.3 %. In scenario 1, where the voltage is fixed and equal to 1 pu in both grids, it is observed a higher reactive power in total, compared to scenario 2, where voltage varies. This can be justified by eq. 4.8 and eq. 4.7, where reactive power in rotor and stator is proportional to the voltage at the rotor side and the stator side, respectively. The fact that reactive power absorbed by the VFT also decreases in scenario 2 compared to scenario 1, is explained by the assumption that a lower power flow through the machine, leads to a lower current in the magnetizing branch.

4.4.2 Case 3: Weaker grid interconnection between synchronous systems, and capacitor bank compensation

Reactive power and voltage in a power system are strongly connected. The reactive power supplied/consumed by a grid will lead to a varying voltage, and in worst case lead to voltage collapse. Previous case studies carried out in this thesis implies that the VFT requires reactive power to transmit active power between to synchronous systems. So far this reactive power has been supplied by the two ac grids. It will be interesting to investigate an integrated system of a VFT and a reactive power compensator. In case 3 the performance of the VFT combined with a capacitor bank and a weaker grid interconnection is going to be evaluated in terms of reactive power and voltage stability. Two different scenarios will be evaluated. In the first scenario the weak grid connection will receive power from grid 1 through the VFT. Based on previous simulations it is assumed a reactive power flow in the opposite direction, which means that grid 2 is a supplier of reactive power in this scenario 1. In scenario 1 the influence of switching a capacitor bank in the weaker grid side is going to be examined when active power is being injected into the grid. In scenario 2 the weaker grid is going to be the supplier of active power, which implies that grid 2 will receive reactive power. In scenario 2 a study on the impact of a capacitor bank implemented in power system 1 is going to be carried out.

Scenarios:

1. Weaker grid receiving active power - reactive power compensation by capacitor bank in grid side 2.
2. Weaker grid supplying active power - reactive power compensation by capacitor bank in grid side 1.

Objectives:

- Evaluate the reactive power flows and grid voltage with integrated capacitor bank.
- Obtain a sufficient size of the capacitor bank.
- Study the response of the VFT with a capacitor bank implemented in the system.

Observations:

- Reactive power will flow in the opposite direction of active power.
- Reactive power will affect the voltage in power system 2.
- Voltage in power system 1 is fixed to V_s = 1 pu because of a strong grid connection in this side.
- Capacitor bank will compensate the reactive power supplied by the grid.

Scenario 1: Weaker grid side receiving active power - compensation by capacitor bank in grid side 2.

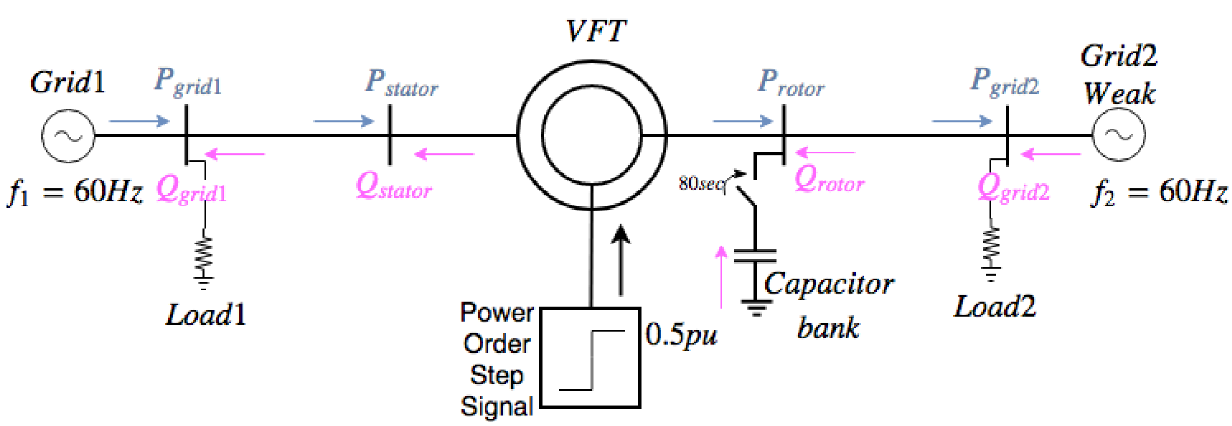

Figure 4.7: Model topology for scenario 1, including power flow direction and placing of the capacitor bank.

Figure 4.7 illustrates a single line diagram of the system analyzed in scenario 1 with a capacitor bank implemented at grid side 2, i.e. the rotor side. Grid 1 is a strong grid modeled by an ideal source. Grid 2 is modeled by a non-ideal source of 50 GVA and a X/R-ratio of 15 to make it slightly weaker. Both grids operate at 60 Hz. A capacitor bank is implemented in grid side 2 with the aim of providing the necessary amount of reactive power to the system.

Procedure:

- Power order step signal of 0.5 pu applied at 50 seconds. Thus, active power flows from grid 1 to grid 2.
- Initially a simulation with no reactive compensation is carried out.
- Next a simulation with a capacitor bank switched in at 80 seconds is carried out. The capacity of the reactive capacitor bank is 0.9 pu, corresponding to 90 MVar.
- The sizing of the capacitor bank is based on the amount of uncontrolled reactive power flow when no compensation is present in the system.

The two figures 4.8 and 4.9 presents the reactive power flows in power system 2, including grid 2 and the rotor windings of the VFT. The green line is the initial case, where no reactive power compensation is present. The purple line represents the reactive power when a capacitor bank is implemented in grid side 2. The green curve is positive for the whole simulation period, indicating that grid 2 supplies reactive during this period. With no compensation of Q, the reactive power supplied by grid side 2 increases from 0.2 pu to 0.8 pu at 50 seconds, when the active power transfer starts. The resulting voltage profile in the weaker grid connection is presented in fig. 4.10. It can be observed a voltage sag at 50 seconds, where voltage decreases from 0.9997 pu to 0.9985 pu. At 80 seconds the capacitor bank is switched in and the voltage curve increases up to approximately 1 pu. This is still a relatively strong connection, hence voltage variations are small. However, one of the objectives of this case study is to evaluate the VFT reactive power performance during voltage variations and not a worst-case scenario.

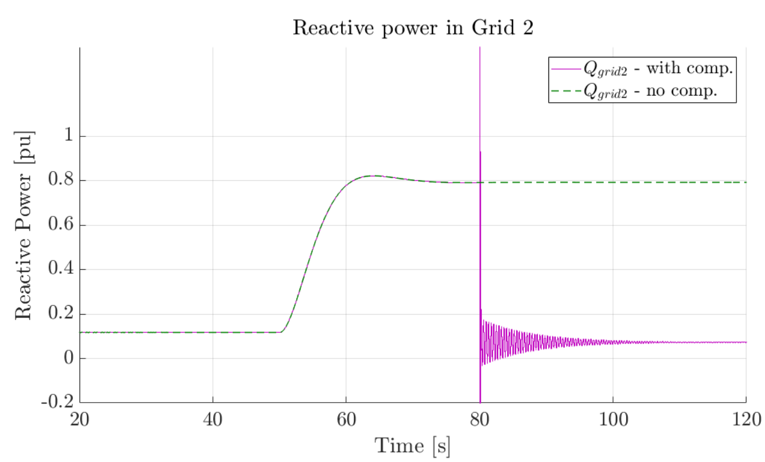

Figure 4.8: Case 3, Scenario 1: Reactive power in grid 2. Green line - no reactive compensation. Purple line - with reactive compensation.

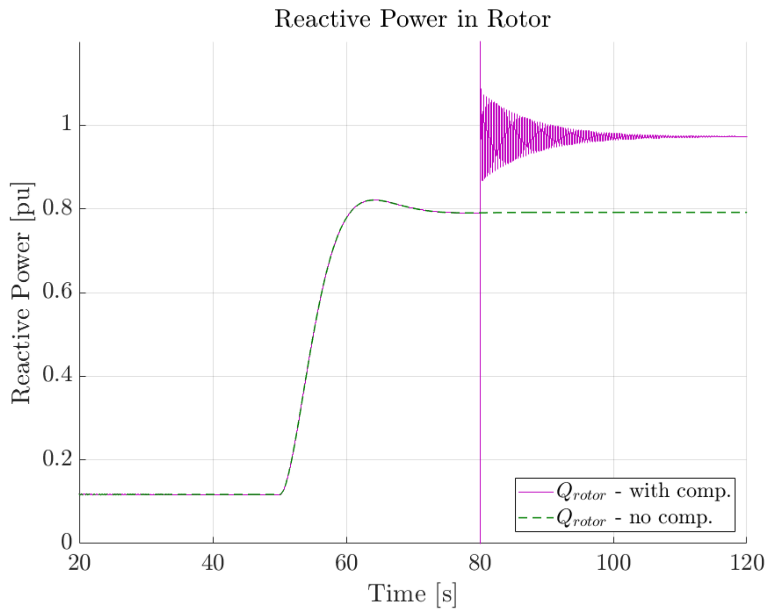

Figure 4.9: Case 3, Scenario 1: Reactive power in rotor. Green line - no reactive compensation. Purple line - with reactive compensation.

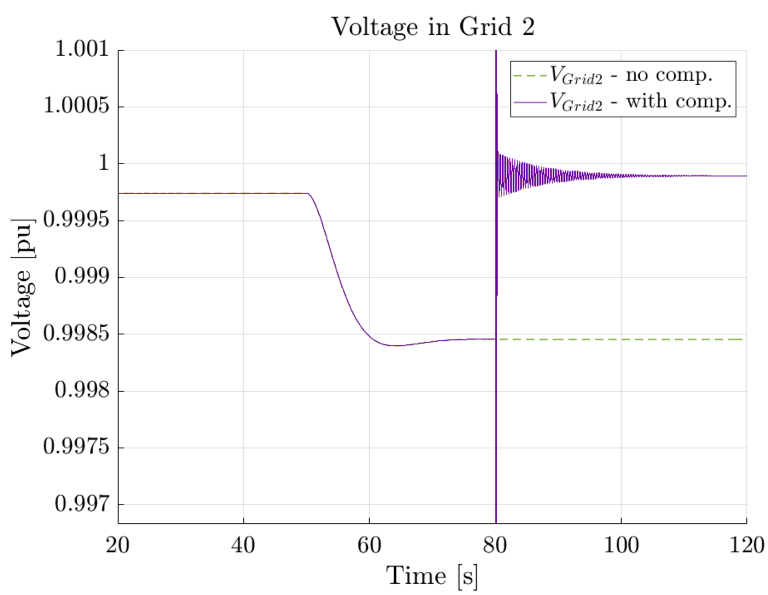

Figure 4.10: Case 3, Scenario 1: Voltage profile in the weaker grid 2. Green, dashed line - no reactive compensation. Purple line - with reactive compensation.

The purple curves in fig. 4.8 shows the result in reactive power flows when a 0.9 pu capacitor bank is introduced in the system. At 80 seconds the capacitor bank is switched in, and an instant drop of approximately 0.7 pu reactive power in grid 2 is observed. At the same time, the reactive power flowing to the VFTs rotor windings increases with almost 0.2 pu. In fig. 4.10 it is observed a voltage increase at the moment of switching the capacitor bank. The voltage recovers to its nominal value, which is the purpose of providing reactive power compensation. The reason for the reactive power drop in grid 2 is due to the reactive power compensation provided by the capacitor bank. The increase in reactive power in the rotor windings of the VFT, seen in fig. 4.9, can be explained by the voltage increase in the grid side. From Eq. 4.8 it is stated that Q in the rotor is proportional to the voltage at the rotor terminals. Additionally, the requirement of reactive power in the VFT is determined by the voltage in each side of the machine, and the inductance of the machine. Hence, a higher voltage in either side leads to a higher amount of reactive power flow.

The reactive power characteristics in power system 1, including stator windings and grid 1, are presented in fig. 4.11. The green line presents the initial case, with no reactive power compensation, while the purple curve presents the case with a capacitor bank switched in at 80 seconds. A first observation is that the reactive power flow in grid 1 and stator windings is the same, as the curves in the two plots are similar. The negative polarity of the reactive power indicates that it flows away from the VFT, indicating that for this situation the reactive power supplied by grid side 2 is injected into grid 1. The purple curve, reactive power in the stator and grid 1, is the inverse of the reactive power in the rotor fig. 4.8. Thus the power flowing into the rotor flows out of the stator and to grid 1. The only difference is the magnitude, as some reactive power is absorbed by the VFT.

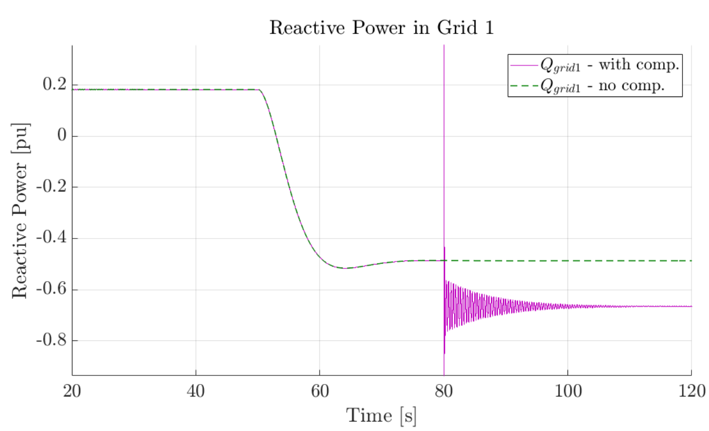

Figure 4.11: Case 3, Scenario 1: Reactive power in grid 1. Green line - no reactive compensation. Purple line - with reactive compensation.

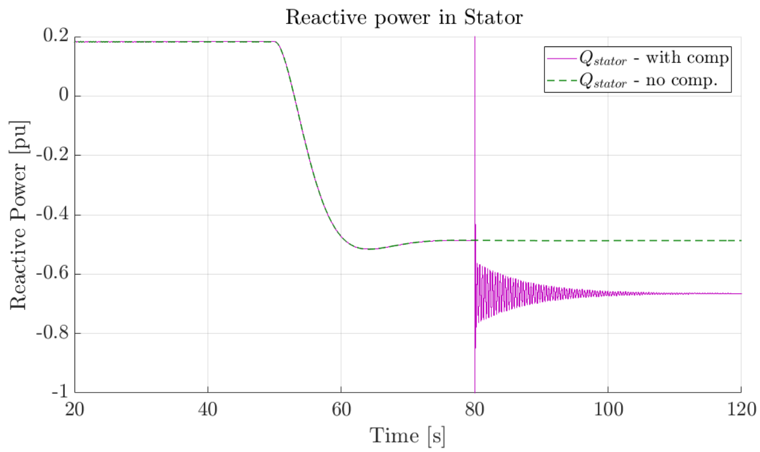

Figure 4.12: Case 3, Scenario 1: Reactive power in stator. Green line - no reactive compensation. Purple line - with reactive compensation.

As a result of installing a 0.9 pu capacitor bank at the stator terminals of the VFT the reactive power requirement of the system is more or less covered by the compensator. Thus, the weaker grid connection does not need to provide reactive power, and terminal voltage can be maintained within an acceptable range. Figures showing the active power flows can be found in appendix A.

Scenario 2: Weaker grid supplying active power - compensation by capacitor bank in grid side 1.

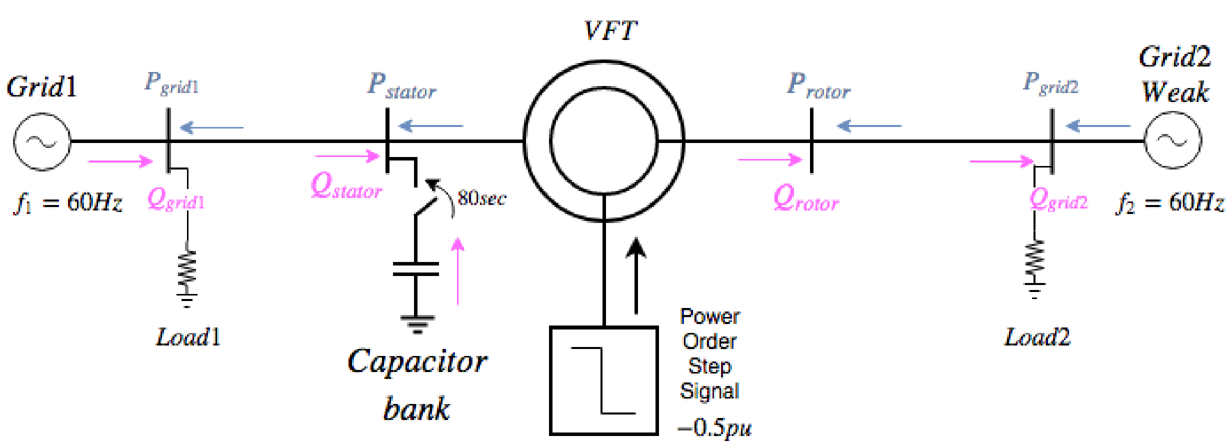

Figure 4.13: Model topology for scenario 2, including power flow direction and placing of the capacitor bank.

In scenario 2 the reactive power characterization of the system is going to be evaluated in terms of reactive compensation in power system 1. In this scenario the weaker grid will be the supplier of active power, thus receiving reactive power, as shown on fig. 4.13. The capacitor bank is placed close to the VFT in grid side 1. The procedure of the study is the same as for scenario 1.

Procedure:

- Power order step signal of -0.5 pu applied at 50 seconds. Thus, active power flows from grid 2 to grid 1.
- Initially a simulation with no reactive compensation is carried out.
- In next simulation a capacitor bank is switched in at 80 seconds. The capacity of the reactive capacitor bank is 0.86 pu, corresponding to 86 MVar.
- The sizing of the capacitor bank is based on the amount of uncontrolled reactive power flow when no compensation is present in the system.

The green, dashed lines in figures 4.14 - 4.17 illustrates reactive power in the system for the initial situation, with no reactive power compensation. While the purple curves illustrate the reactive power flowing through the system when a capacitor bank is installed close to the VFT at grid side 1. In both simulations, 0.5 pu of active power is transmitted from the weaker grid (grid 2) to the strong grid (grid 1). Figure 4.14 illustrates the reactive power in grid 1, it is observed an instantaneous drop in reactive power at 80 seconds, when the capacitor bank is switched in.

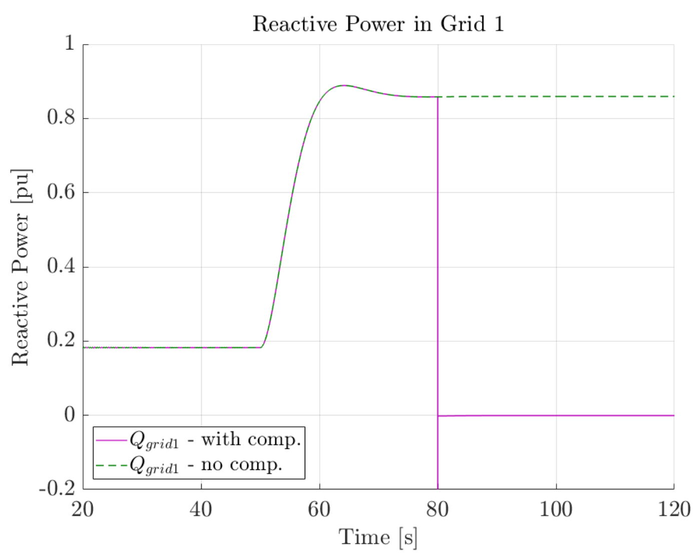

Figure 4.14: Case 3, Scenario 2: Reactive power in grid 1. Green line - no reactive compensation. Purple line - with reactive compensation.

The purple curve drops to zero, which means that all of the required amount of reactive power is provided by the capacitor bank. The reactive power flowing into the stator windings, shown in fig. 4.15, does not experience any change in reactive power when the capacitor bank is switched in. This is because the exact same amount of reactive power flows through the VFT, and the machine does not care where the reactive power comes from, as long as the required amount of Q is delivered.

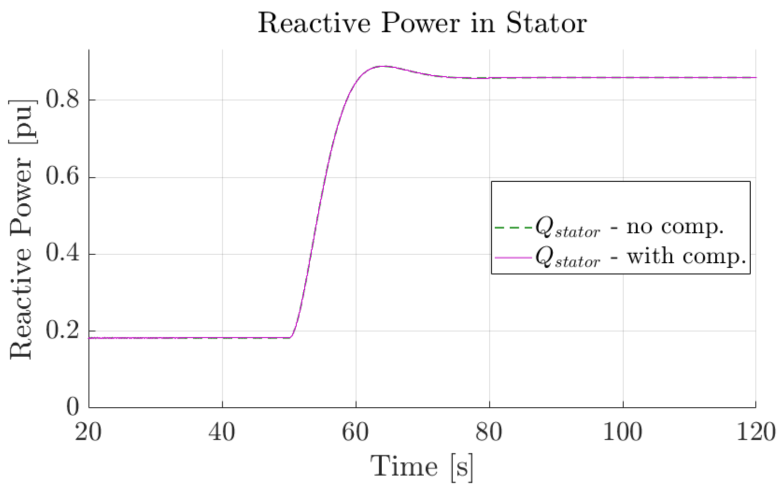

Figure 4.15: Case 3, Scenario 2: Reactive power in stator. Green line - no reactive compensation. Purple line - with reactive compensation.

In fig. 4.16 and 4.17 the reactive power in grid 2 and the rotor windings is presented. The green and purple curves are identical, implying that the effect of a capacitor bank in power system 2 does not impact the reactive power in grid side 1.

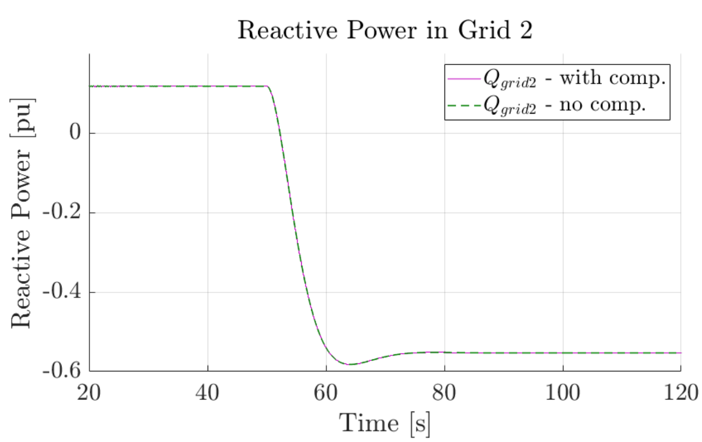

Figure 4.16: Case 3, Scenario 2: Reactive power in grid 2. Green line - no reactive compensation. Purple line - with reactive compensation.

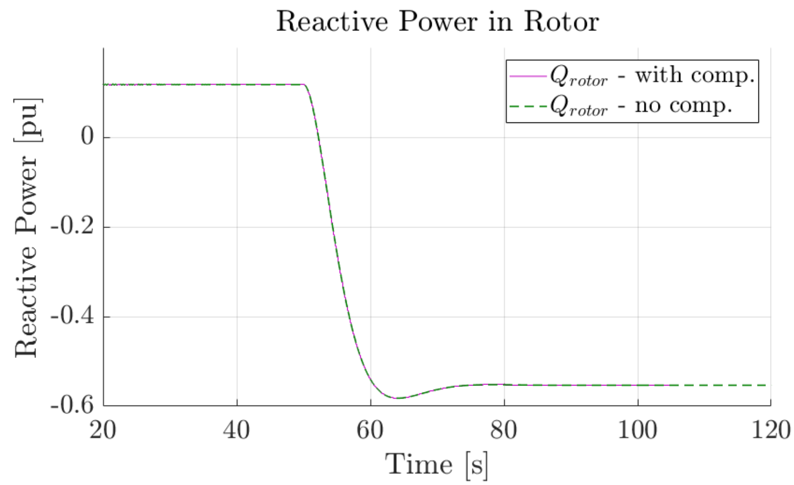

Figure 4.17: Case 3, Scenario 2: Reactive power in rotor. Green line - no reactive compensation. Purple line - with reactive compensation.

The amount of reactive power flowing into the stator windings of the VFT minus the consumed reactive power of the machine, equals reactive power flowing out of the stator windings. This amount of reactive power is injected into the weaker grid 2. This reactive power injection affects the voltage in the grid as observed in fig. 4.18. Figure 4.18 represents the voltage variation in grid 2. At 50 seconds 0.55 pu of reactive is being fed to the grid, as a result of this the voltage experience a rise in magnitude. Figures showing the active power flows can be found in appendix A.

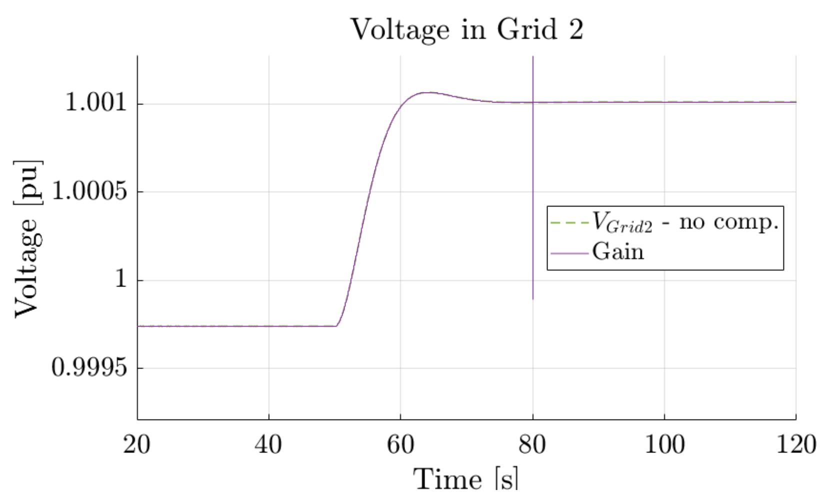

Figure 4.18: Case 3, Scenario 2: Voltage profile in the weaker grid 2. Green, dashed line - no reactive compensation. Purple line - with reactive compensation.

4.4.3 Case 4: Asynchronous grids, weak grid, capacitor bank

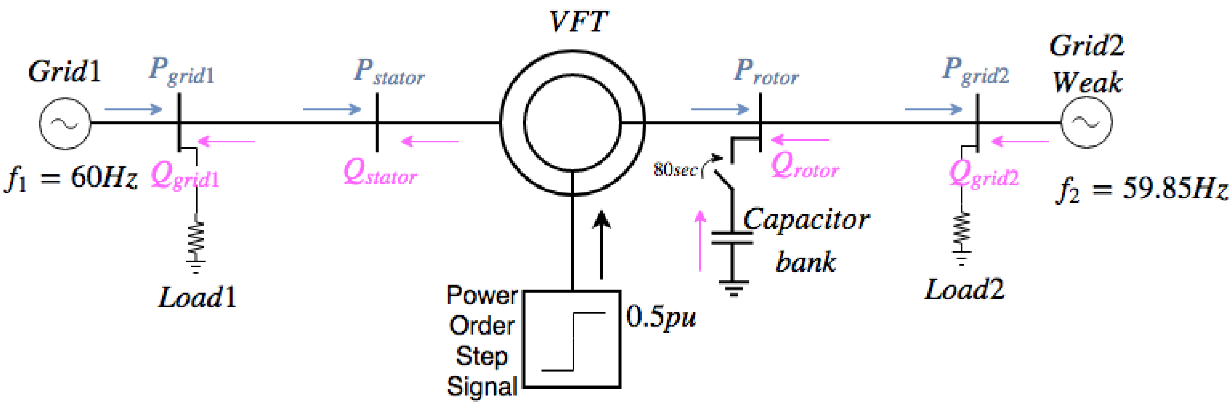

Figure 4.19: The single line diagram for case 4, including power flow directions.

One of the most interesting aspects of the Variable Frequency Transformer is its capability to transfer power between asynchronous power systems. In reality, small deviations in the nominal system frequency will occur, as frequency is strongly dependent on the balance between generation and loads in the network. This case study will evaluate the reactive power requirement in the system when the VFT is used as an interconnection of grids operating at a frequency difference of 0.25%. The model topology used in this case study is presented in fig. 4.19. Grid 1 is a strong network operating at 60 Hz, while grid 2 is a weaker network operating at a frequency of 59.85 Hz.

Objectives:

- Investigate the behaviour of the VFT in terms of reactive power requirements and voltage variations when it is operating as an interconnection between asynchronous systems.
- Evaluate the effect of implementing a capacitor bank in the power system supplying reactive power.
- Obtain a sufficient size of the capacitor bank.

Observations:

- The rotor will start spinning due to the difference in frequency between the two grids. Slip, active and reactive power will be affected.
- Reactive power will flow in the opposite direction of active power.
- Reactive power will affect the voltage in power system 2.
- Voltage in power system 1 is fixed to V_s = 1 pu because of a strong grid connection in this side.
- Capacitor bank will compensate the reactive power supplied by the grid.

Procedure:

- Frequency in strong grid 1 = 60 Hz. Frequency in the weaker grid 2 = 59.85 Hz.
- First, an initial simulation, with no capacitor bank implemented, is carried out.
- Power order step signal of 0.5 pu applied at 50 seconds. Thus, active power flows from grid 1 to grid 2.
- Next simulation contains a 120 MVar capacitor bank in grid side 2, which is switched in at 80 seconds.

The figures 4.20-4.23 represent the reactive power flows in the system, including the strong grid 1, stator windings, rotor windings and the weaker grid 2. The initial case, with no reactive power compensation in the system, is represented by the green, dashed line. The purple curves illustrates the case when a 1.2 pu capacitor bank is connected in power system 2, close to the VFT. Even though the frequencies are different in the two networks connected by the VFT, stable operation is maintained. From fig. 4.20 it is observed that the reactive power flowing from grid 2 is positive during the whole simulation period, indicating that reactive power flows from grid 2 towards the VFT. In fig. 4.21 it is observed that the exact same amount of reactive power flowing from grid 2 flows in the rotor windings of the VFT, as expected. At approximately 50 seconds a rise in reactive power is observed. At this point the VFT starts transferring 0.5 pu of active power from grid side 1 to grid side 2, through the machine.

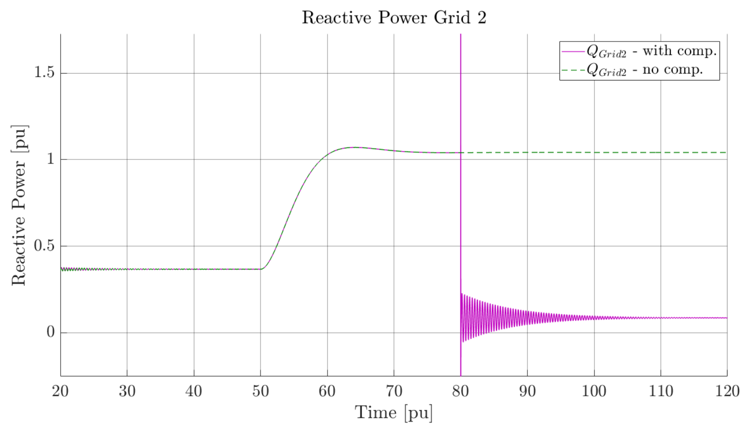

Figure 4.20: Reactive power in grid 2. Green line - no reactive compensation. Purple line - with reactive compensation.

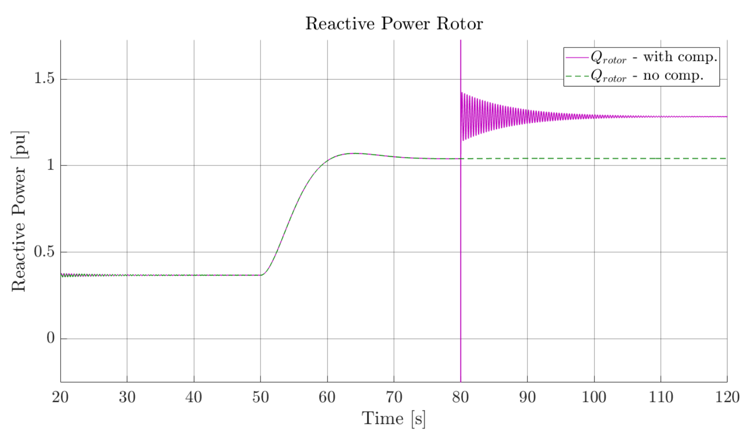

Figure 4.21: Reactive power in rotor. Green line - no reactive compensation. Purple line - with reactive compensation.

From fig. 4.22 and fig. 4.23 it is observed a negative power flow of approximately 0.1 pu during the first 50 seconds. The negative polarity means that reactive power is flowing from the VFT stator windings and to grid 1. After 50 seconds 0.5 pu of active power is flowing through the VFT and the value of reactive power flowing to grid 1 decreases to -0.75 pu. Hence, more reactive power is injected to grid 1. The large amount of reactive power being injected to grid 1 is supplied by the weaker grid 2. As a result of this the voltage in grid 2 experience a voltage drop during the time period from 50 to 60 seconds, as the reactive power supply builds up, this situation is observed by the green, dashed line in fig. 4.24.

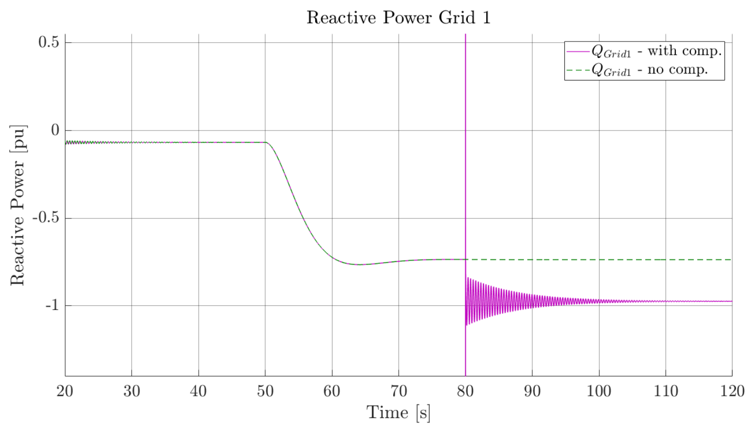

Figure 4.22: Reactive power in grid 1. Green line - no reactive compensation. Purple line - with reactive compensation.

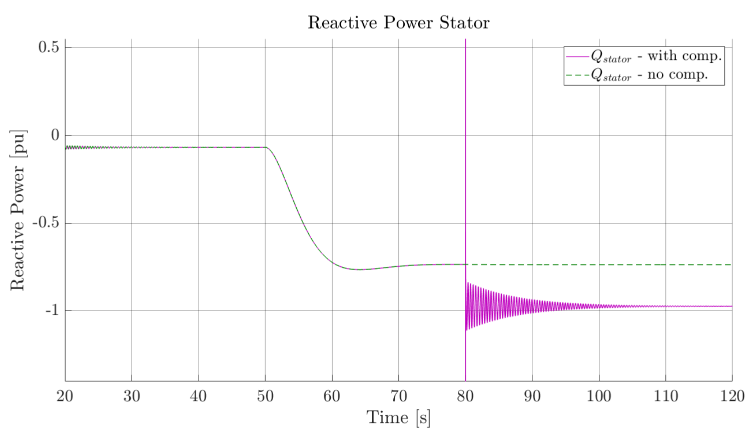

Figure 4.23: Reactive power in stator. Green line - no reactive compensation. Purple line - with reactive compensation.

A solution to counteract the voltage drop in the weaker grid is to implement reactive power compensation. Voltage an reactive power is strongly dependent on each other, and control of one parameter can be used to regulate the other. The purple line in fig. 4.20 shows that the reactive power supplied by grid 2 instantaneously decreases to zero when the capacitor bank is switched in at 80 seconds. This is due to the fact that the reactive power requirement of the system is completely compensated by the capacitor bank. At the same time, the voltage profile of grid 2 increases to a stable magnitude of 1 pu, illustrated by the purple curve in fig 4.24. For the rest of the system, including rotor and stator windings of the VFT, and grid 1, an increase of approximately 0.3 pu of reactive power is observed in the moment the capacitor bank is switched in. This is illustrated by the purple curves in fig. 4.23, fig. 4.21 and fig. 4.22. The 0.3 pu increase of reactive power can be explained by the increased voltage in grid 2, which induces a higher amount of reactive power requirement of the machine. As reactive power is determined by the voltages on each side of the VFT and the impedance of the machine. From fig. 4.22 it is seen that grid 1 has to absorb 1 pu of reactive power after the capacitor bank is switched in. In this simulation model, grid 1 is represented by an ideal source, corresponding to a strong network. Thus, the effect of the high amount of reactive power injection to the grid is not detected in this simulation. However, in a more realistic study, the voltage in grid 1 may experience an increase in magnitude due to the reactive power.

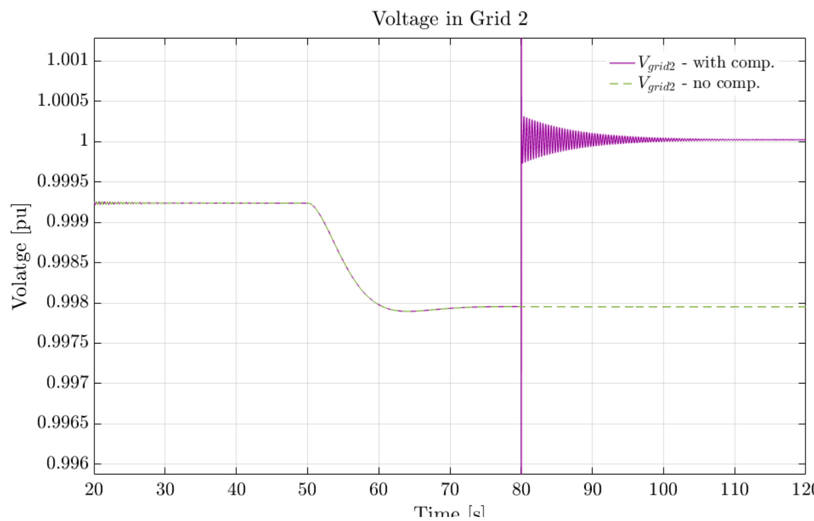

Figure 4.24: Voltage profile in the weaker grid 2. Green, dashed line - no reactive compensation. Purple line - with reactive compensation.

Comparing this case to Case 3, described in section 4.4.2, where the grids operate at the same frequency, the total amount of reactive power is higher. A frequency difference of 0.25% leads to a reactive power increase of 37.5% compared to case 3 with synchronous grids. The magnitude and direction of active power are the same for the two cases compared here. When a small frequency deviation is present, the rotor will move continuously with a rotational speed proportional to the frequency difference. This is to obtain synchronization between the stator and rotor fluxes in the air-gap. The VFT requires more reactive power to build up and sustain the flux fields in the machine when there is a frequency difference in the tie. In order to compensate the reactive power demand of the system, the capacitor bank needs to be larger compared to the capacitor bank in case 3. In the asynchronous interconnection investigated in this case, the voltage in the weaker grid experience a deeper sag in magnitude compared to case 3 with synchronous systems. It is plausible to assume that this is related to the increased demand of reactive power from grid 2 (the weaker grid). Figures showing the active power flows for case 4 can be found in appendix B.

4.5 Summary

This chapter analyze the reactive power characterization and requirements of the VFT. By means of electromagnetic induction active power is transferred through VFT. Results showed that theVFT consumed approximately 0.3 pu of reactive power in order to build up and maintain the magnetic flux fields required for active power transfer. Case studies showed that the reactive power required for maintaining the flux fields increased with the amount of active power exchanged through the VFT.

The VFT provides a path for reactive power exchange between the two interconnected networks and the machine is unable to fully control these power flows alone. Case studies implies that the reactive power exchange is dependent on the magnitude and direction of the active power exchange. Results showed that the reactive power requirements are higher for the asynchronous case compared to the synchronous case. The considerable amounts of reactive power affected the grid voltage in the weaker network. Injection of reactive power to the grid lead to a voltage rise in the grid and when the grid supplied reactive power a voltage sag was observed. A passive capacitor bank was implemented in the system and it manged to fully compensate the reactive power requirements and bring the voltage to its nominal value.

Chapter 5

VFT Reactive Power Compensation using a STATCOM

By means of appropriate reactive shunt compensation the steady-state transmittable power can be increased, and the voltage profile controlled. Shunt connected reactors can be implemented to diminish line overvoltage during light load conditions. Shunt connected capacitors can be implemented to preserve voltage levels under heavy load conditions [32]. The main objective of applying reactive shunt compensation in a power system is to increase the power transmission, hence improve the power factor of the system [39].

In recent years the technological advancement in power electronics has assisted in the development of power electronic equipment with the ability to handle large amounts of power. These power electronic devices belongs to the group called Flexible AC Transmission System (FACTS), and are based on electronic power. The main task of the FACTS is to control and adjust the electrical power system [39]. Additional benefits including improved stability and efficiency of the grid, and control of power flows can also be provided by FACTS components. Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are well established FACTS equipment used for generation and absorption of reactive power. The VFT is able to control the real power flow, and it can supply reactive power from one grid to the other. However, shortage of reactive power flow control is the reason why VFT is not able to provide perfect isolation between grids [2]. An alternative solution using STATCOM combined with the VFT is suggested and investigated theoretically in this chapter.

5.1 Reactive Power Compensation

Shunt capacitor banks and different FACTS devices, such as Static Var Compensators and STATCOMs, can be used to compensate for the reactive power demand of the VFT. The output from the SVC and STATCOM is varied to preserve or control specific parameters of the power system, with a main objective to increase power transfer capability of the system [32]. The static compensators (SVC and STATCOM) can neither absorb or generate real power, thus the power transmission capability of the system is indirectly affected by voltage control. This means that the reactive power output from the compensator is varied to obtain a desired voltage level during possible system disturbances. At the same time the desired power flow is maintained.

5.1.1 Static Var Compensator - SVC

IEEE definition: ***Static Var Compensator:*** *A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)* [32]
The Static Var Compensator is a well known FACTS equipment, and one of the most used technologies for reactive power compensation today. A SVC is a shunt connected static var generator or absorber whose main task is to exchange inductive or capacitive current with the power network, in order to control or maintain specific parameters [39]. The working principles of a SVC is similar to a variable shunt susceptance. It uses fast thyristor controllers with very short settling time, only a few fundamental frequency periods. The SVC can draw either capacitive or inductive current from the network, and by a sufficient control scheme of the SVC, it is possible to regulate the voltage magnitude at the connection point. By voltage regulation the system performance increase significantly, due to the fact that voltage regulation prevent large voltage variations and voltage collapse, voltage regulation also increase the transient stability limit and it provides damping of power oscillations.

As previously mentioned the SVC is based on thyristors, but the design can vary in many different ways. However, the most typical arrangements of a SVC consists of fixed capacitors (FC) combined with Thyristor Controlled Reactor (TCR), or a Thyristor Switched Capacitor (TSC) with a TCR [32]. The controllable thyristors can provide a smooth control of the TCR in the range of 90-180 °. The TSC is a fast switched element which obtains voltage regulation in a stepwise mode. A TCR single-phase equivalent circuit is presented in fig. 5.1. By means of conduction control of the bi-directional thyristor valves the shunt reactor is dynamically controlled. The thyristor switching controls the parallel connection of the shunt capacitive reactance X_C and the inductive reactance X_L, thus the SVC can be seen as a variable shunt reactance. [39]

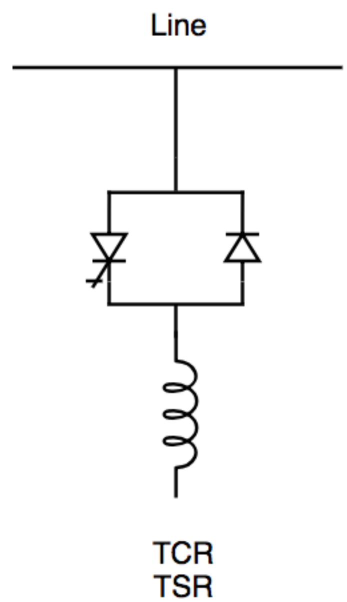

Figure 5.1: Static Var Compensator equivalent circuit

5.1.2 Static Synchronous Compensator - STATCOM

IEEE definition of ***Static Synchronous Compensator:*** *A Static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the AC system voltage* [32].

The Static Synchronous Compensator (STATCOM) is a power electronic device and a part of the Flexible AC Transmission System (FACTS) group. The objective of a STATCOM is the same as for the SVC, to provide reactive shunt compensation to control the voltage profile along a line and to increase the steady state active power transfer [32]. A STATCOM is a device used for providing fast and continuous capacitive and inductive reactive power to the system [2]. This will also lead to increased power transfer capability of the network. In addition, the FACTS device can be used to improve stability of the interconnection of AC power systems [43]. The STATCOM has no ability to store energy, hence it can not absorb nor generate active power [44]. This means that the power transmission of the system is affected indirectly by voltage control. It can supply or absorb reactive power in a regulated way independent of the AC system voltage, and thereby increasing the stability of the system. An equivalent circuit of a STATCOM is presented in fig. 5.2. The STATCOM is a VSC-based device, where the voltage source is placed behind a reactor. There are two variants of STATCOMs, presented in fig. 5.2, one based on current-source converter (CSC) and the other based on voltage-source converter (VSC)/voltage-source inverter (VSI). In the following only the latter will be considered.

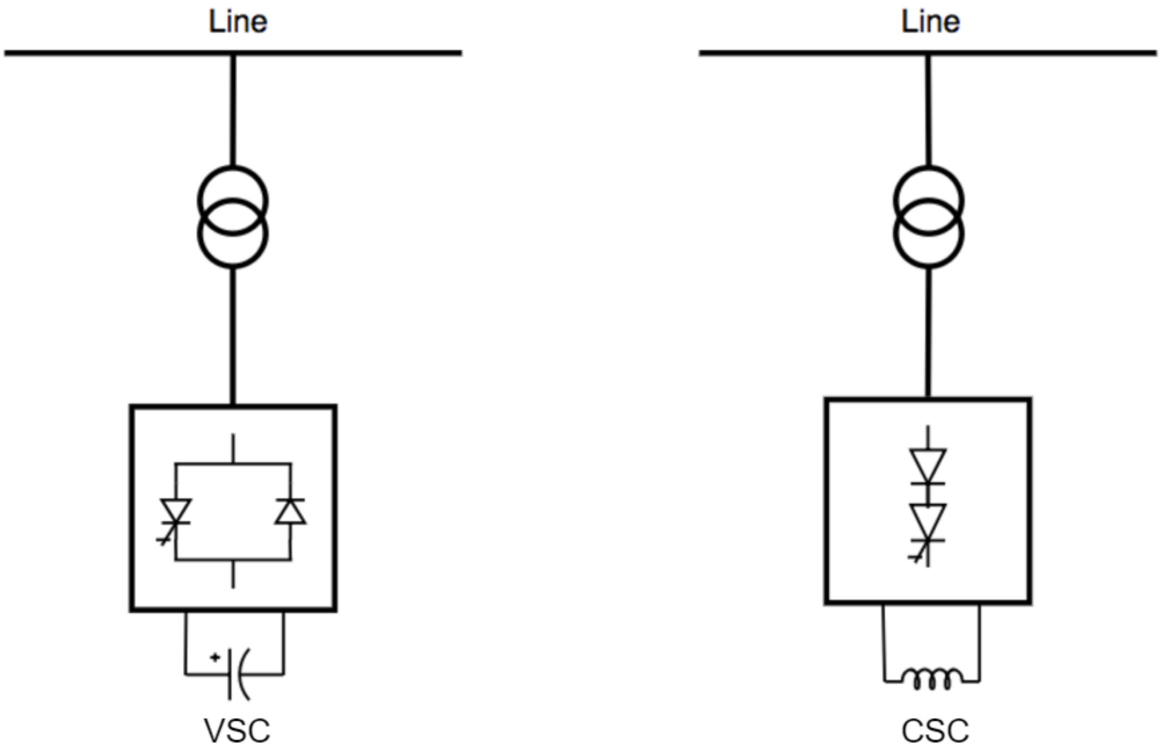

Figure 5.2: Static Synchronous Compensator equivalent circuit

The VSC-based STATCOM consists of an three-phase inverter which are controlled by Pulse Width Modulation (PWM). In the traditional compensators, such as compensators, the size of the capacitance is directly related to the capacity of the reactive capacitor. The DC-link of the STATCOM has no direct connection to the capacity of the reactive compensation. The value of the DC-voltage, V_{dc} can be calculated by means of the following equation [43]:

$$V_{LL} = \frac{\sqrt{3}}{2\sqrt{2}} m V_{dc} \tag{5.1}$$

Where V_{LL} is the line to line voltage at the PCC and m is the modulation index. When m is in the range $0 < m < 1$, the linear relationship between the input and output PWM voltage is maintained. The relationship between the current, I_c and voltage, V_{dc} across the capacitor is:

$$C \frac{dV_{dc}}{dt} = I_c \tag{5.2}$$

Here C is the capacitance in Farad. For a detailed elaboration of the basic operation of the STATCOM, see [43].

5.1.3 Comparison of STATCOM and SVC

The application of a STATCOM is similar to the SVC. The main difference between the two devices is the how they operate. A STATCOM works in the same way as a voltage source converter. The SVC operates as a dynamically controllable reactance connected in parallel. The STATCOM provides the possibility to feed the grid with maximum available reactive current even for lower voltages. This is possible due to linear relationship between reactive power and voltage for every equilibrium situation at the PCC [45], as shown in fig. 5.3. Figure 5.3 illustrates the relationship between the voltage magnitude and reactive power at the PCC for the STATCOM and for the SVC. In comparison, for the SVC there is a quadratic relationship between the reactive power and voltage in the PCC [46]. In short this means that the SVC requires a higher capacity than the STATCOM to be able to provide the same amount of reactive power as the STATCOM. Figure 5.4 represents the voltage and current relationship at PCC for the STATCOM and the SVC. It is observed that the STATCOM has a higher capability of providing current compensation compared to the SVC. Even for low voltages the STATCOM is able to provide full rated reactive current to the system. Another aspect of the STATCOM is its ability to store real power in the DC-link capacitor. In contrast to the SVC the STATCOM has a much faster response [47]. Thus switching losses are higher for the STATCOM. The STATCOM is a more complex device and the installation costs are higher than for the SVC. In total, in a comparison between the two FACTS-devices the STATCOM is proven to be the preferred solution for most situations. Table 5.1 lists some of the pros and cons related to each of the two reactive power compensators.

Table 5.1: A comparison of STATCOM and SVC

STATCOM	**SVC**
Shunt connected	Shunt connected controlled
synchronous voltage source	reactive admittance
Faster response	Slower response
Higher losses	Lower losses
Smaller in size	Larger in size
Higher costs	Lower costs
Higher voltage support capability	Lower voltage support capability

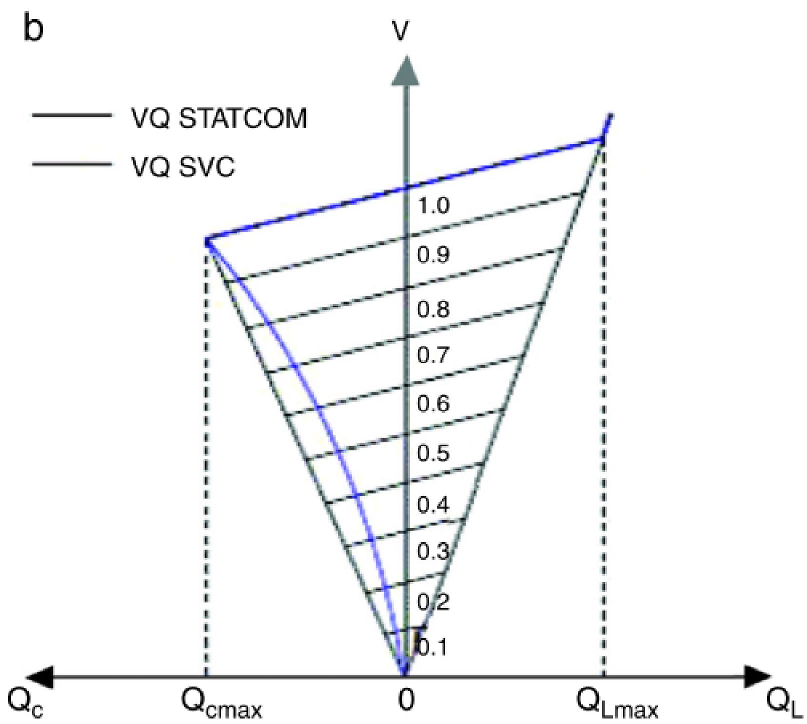

Figure 5.3: The VQ-curve of a STATCOM and SVC [46].

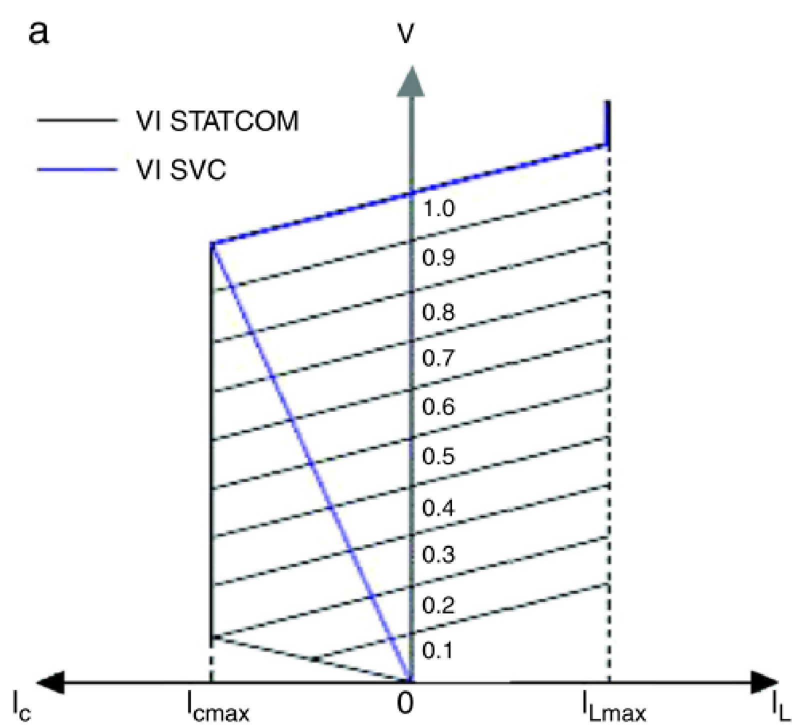

Figure 5.4: The VI-curve of a STATCOM and SVC [46].

From an operational point of view the STATCOM is superior to the SVC in terms of performance, application flexibility and stability. Thus, it is chosen to further investigate the possibility of collaborating the VFT and STATCOM to compensate the reactive power needs of the machine.

5.2 VFT-STATCOM combined system

As previously mentioned, the VFT controls the active power flow through the machine and it provides a path for reactive power flows. However, the machine is unable to control the reactive power, making it inadequate to provide quality power. A possible solution by implementing a STATCOM to support the VFT with reactive compensation is presented in this section. Some basic theory of the STATCOM was presented in section 5.1.2. Further the characteristics of a STATCOM in a VFT system will be considered, including control schemes and position of the STATCOM with respect to the VFT and the two power systems. An overview of the combined VFT-STATCOM system is illustrated in fig. 5.5.

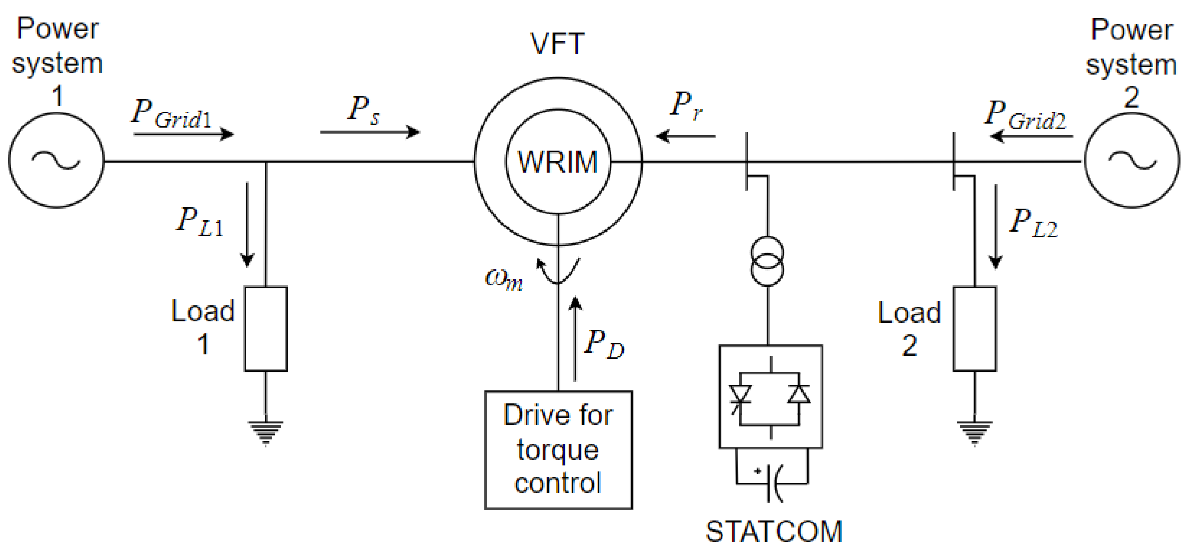

Figure 5.5: The combined system with VFT and STATCOM.

5.2.1 General Control Scheme of the STATCOM

In order to provide the reactive compensation requirements of the VFT, the output of the STATCOM needs to be controlled to change or sustain the voltage at the PCC. There are three regulators in the STATCOM control system, including DC-voltage regulator, current regulator and reactive power regulator. A general control scheme of the STATCOM is shown in fig. 5.6. The outerloop consists of voltage regulation blocks and the inner loop comprises the current regulation. For the control operation the synchronous dq-reference frame is used, see appendix C for detailed description of the dq-transformation. The control system is composed by the following typical blocks:

- DC-link voltage regulator
- AC voltage regulator
- Reactive power regulator
- Current regulator

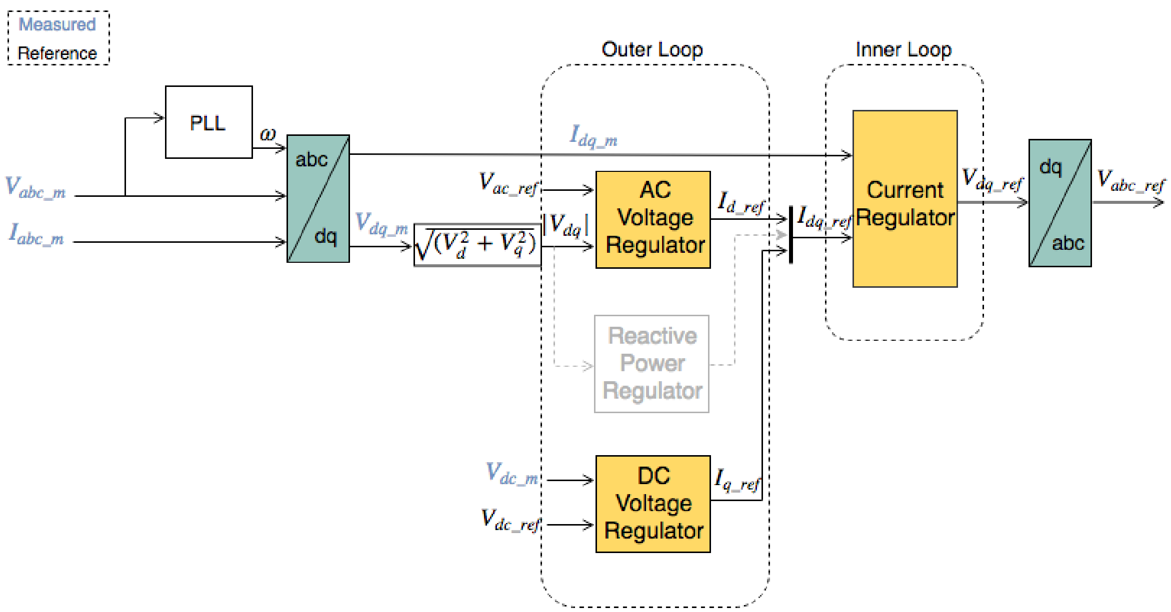

Figure 5.6: General control scheme of a STATCOM

DC-link voltage regulator The DC-link voltage regulator is a part of the outer control loop. The outer control loop of the STATCOM regulates the voltage over the DC-capacitor, and the reactive power exchanged with the grid. The DC-link voltage controller keeps the voltage constant to a specified value. A Proportional Integrator (PI)-regulator amplifies the voltage error of the measured voltage over the DC-link, V_{dc_m}, and the reference voltage V_{dc_ref} and generates a reference signal, i_{d_ref}. i_{d_ref} is sent to the inner control loop (current controller) and represents the active part of the current.

AC voltage regulator The AC voltage regulator is a part of the outer control loop of the STATCOM control scheme. The input parameters to the AC voltage regulator is the magnitude of the measured voltage in dq-reference frame, $|V_{dq\_m}|$. Also the AC voltage regulator comprises a PI regulator which converts the error between the measured voltage and the reference voltage, V_{ac_ref} to obtain a reference current, i_{q_ref}. i_{q_ref} is the reactive part of the current, which is related to the reactive power produced by the STATCOM.

Reactive power regulator The reactive power regulator is an alternative to the AC voltage regulator. It takes in a given reference of reactive power, and compares it to the measured amount of reactive power at the PCC. A PI regulator can be used to obtain the reactive reference signal sent to the current loop.

The AC voltage regulator, combined with the DC-voltage regulator and current regulator, is the common regulating scheme for the STATCOM, and is used for voltage support at the PCC. In a weak grid where voltage will vary as a result of contingencies in the grid, the STATCOM AC regulator is necessary to bring the voltage to its nominal value. In a strong grid, where the voltage is stable and there is need for reactive power compensation the reactive power regulator is an option.

Current regulator In the current controller the real power to be exchanged by the converter is obtained to keep a constant DC-voltage over the capacitor. The current regulator is also denoted as the inner control loop. The measured current in the PCC is converted into dq-reference and sent into the current controller. In the outer loop, consisting of the two voltage regulators, the reference current signal, I_{dq_ref}, is obtained. In the same way as in the voltage regulators, PI-controllers are used to amplify the error of the measured current signal and the reference current signal. The output signal of the current controller is a voltage in the dq-reference frame, which is converted into a three-phase voltage used to synthesize the PWM-voltages. This dynamic control operation is constantly measuring the voltage and current at PCC, and is maintaining voltage stability at the point by generating or absorbing regulated amounts of reactive power to the network.

5.2.2 Location of the STATCOM

A STATCOM can be placed in only one side or in both sides of the VFT. This decision depends on different factors including the price, the necessity and the connected power system. The VFT provides bi-directional power flow and as the case studies in this thesis imply, the reactive power might flow in opposite direction of the active power flow. Thus, compensation may be needed in both sides of the machine. However, the VFT allows for reactive power to flow from one power system, through the machine to support the other power system in need. This reactive power can be generated in the STATCOM, thus a reactive power compensator is only needed in one side of the VFT. The STATCOM can also absorb reactive power, and excessive amounts of reactive power in one grid can flow through the VFT to the STATCOM. The STATCOMs reactive power response is significantly faster than the response of the VFT [11]. This disengagement of response times as well as the separation of controlling inputs makes it possible for the VFT and the STATCOM to be in close electrical proximity to each other without adverse interaction [11].

5.3 Summary

The reactive power requirements of the VFT can be met by means of a STATCOM or a SVC, which are FACTS devises used for reactive power transmission control. The basic operation characteristic shows that the STATCOM is able to provide a better support during faults when reactive current is required. A VSC-based STATCOM in combination with the VFT is chosen to investigate further with the focus on controlling the reactive power flow in the system. Two control schemes comprising of voltage and current regulators is described and illustrated. One scheme is based on AC voltage regulation, and is the suggested choice for weak grid interconnections where the voltage at the PCC might suffer due to large reactive power requirements of the VFT. The STATCOM brings the voltage to its nominal value by injecting or absorbing reactive current. The second control scheme is based on direct reactive power regulation. This solution is proposed in a strong grid interconnection requiring reactive power and where voltages are stable. Using a VFT as a tie-line between two power networks allows both the source and sink sides to benefit from the STATCOM and its ability to provide reactive power support.

Chapter 6

Summary and Conclusion

This chapter summarizes the main findings and observations from the thesis. The case studies have been presented and discussed in separate sections, however, the aim of this chapter is to assemble these observations as a whole.

6.1 Summary

In the first part of this thesis the concept of the Variable Frequency Transformer was investigated. The machine enables a controllable and bi-directional power exchange between asynchronous systems. A summary of the key aspects of the VFT is presented:

The VFT attractiveness

- One of the main advantages regarding the VFT is its ability to exchange power between asynchronous power systems.
- The VFT is based on well-known technologies of the hydro generator and the transformer, making it a simple and robust machine. The high inertia of the VFT helps maintaining system stability during disturbances.
- The VFT collaborates well with other system components and in some situations it can also enhance the operation of these components. Such as STATCOMs, which can, by means of the VFT interconnection, provide reactive power to both power systems tie-lined by the VFT.

A basic model of a 100 MW VFT interconnecting the two power networks was implemented in MATLAB/Simulink. A thorough study was conducted to understand the reactive power requirements of the VFT for different operating conditions in terms of the power flow exchange between the two networks.

Active and reactive power flows

- The active power exchange between the two networks showed a linear relationship to the torque applied to the rotor shaft of the machine. In the simulations the torque was represented by a power order step signal.

- In addition to the active power exchange of the VFT, the machine also provide a path for reactive power, which is not fully controllable.

- The analysis in case study 2, see sec. 4.4.1, showed an increase in magnitude of reactive power flow as the magnitude of active power exchange increased. It was also observed that the direction of reactive power flow is opposite from the active power flow, and when active power flow is reversed, so is the reactive power. Hence, it is assumed that both magnitude and direction of active power determines the reactive power flow in the system.

- The consequence of 0.25% frequency deviation between the two asynchronous networks resulted in almost 40% increase in total reactive power requirement of the VFT compared to synchronous conditions.

- If the reactive power exchange through the VFT exceeds the rating capability of the machine, there will be no efficient active power transfer. The significant amounts of reactive power exchange through the VFT might also damage the machine due to excessive currents and overheating of the windings.

Two solutions has been investigated to provide reactive power compensation, namely electromechanical capacitor bank and power electronic based STATCOM. The operation of a capacitor bank is static, and not as flexible as certain power systems require. The STATCOM is a dynamic device which regulates the voltage at the connection point by injecting or absorbing reactive current.

Reactive power compensation

- Simulation results showed that reactive power compensation by means of passive capacitor banks was able to improve system capacity and bring grid voltage to its nominal value.

- An active compensation by a STATCOM was investigated and a voltage regulation control scheme was suggested for implementing the STATCOM and the VFT in a weak grid interconnection.

- A combined system of a STATCOM and a VFT for power exchange between two networks enables both source and sink side to benefit from the reactive power support of the STATCOM.

The Variable Frequency Transformer shows satisfying results in control of the active power flow between asynchronous power systems. The VFT is based on well-known technology of rotating machines and hydro generators, which are known for long service time, and less failing. Thus, it is assumed that the VFT can ensure a more reliable power flow between two power networks compared to power electronic devices which are more likely to fail. On the other hand, the VFT does not provide a decoupled connection between the two networks, such that the HVDC-link does by converting from AC to DC and back to AC. The advantage of a decoupled connection is that a fault does not propagate through the connection and into the other network. The VFT is unable to provide a fully decoupled connection, however, the large inertia and slow response time of the machine might damp the oscillations to some extent.

6.2 Conclusion

The aim of this Master's thesis was to investigate the Variable Frequency Transformer concept and to provide an understanding of the reactive power behaviour of the machine. The VFT enables an interconnection of two asynchronous power systems where active power exchange can be controlled. In addition, the VFT features a path for reactive power exchange that is not fully controlled.

To provide an understanding of the principle operation of the VFT under different operating conditions a MATLAB/Simulink model of the machine was developed. Simulations showed that magnitude and direction of active power exchange between both synchronous and asynchronous networks were controlled by adjusting torque applied to the rotor shaft of the machine. For the VFT to be able to transfer the desired amount of active power between the two networks a certain amount of reactive power is required. Based on simulation results it is assumed that the reactive power requirements of the VFT is depending on the magnitude and direction of the active power exchange. For the asynchronous case, it was observed considerable amounts of reactive power compared to the synchronous case.

In a weaker grid interconnection, the VFTs requirement for reactive power might challenge the voltage stability of the network. By means of a switched capacitor bank, the reactive power requirements of the VFT was met and the grid voltage was brought to its nominal value.

The thesis also evaluated the dynamic compensation of a VSC-based STATCOM as a possible solution to support the reactive power requirements of the VFT and enhance voltage stability. The dynamic control operation of the STATCOM is constantly measuring the voltage and current at the PCC and is maintaining voltage stability at the point by generating or absorbing regulated amounts of reactive power to the network. In a VFT-STATCOM combined system, both networks interconnected by the VFT will benefit from the reactive power support of the STATCOM as the VFT provides a path for reactive power exchange.

6.3 Suggestions for future work

It is strongly encouraged to further extend the VFT model in a more realistic power system, and to evaluate the system performance. Some suggestions for further work on the topics covered in this thesis are listed below:

- A more analytic approach to determine the reactive power flow exchanged in the VFT should be developed. The dq- transformation is a common methodology for rotating machines, and might be a feasible option.
- The DC-motor and the variable speed drive control system should be developed and implemented in the simulation model.
- Both of the AC grids in the simulation model should be replaced by non-ideal sources. This is to simulate a more realistic power system where grid voltages and system stability are critical aspects.
- It is encouraged to study the performance of the VFT as an interconnection between grids with a larger frequency deviation than 0.25 %.
- Develop the simulation model with the STATCOM and the proposed control scheme.

So far the VFT has proven to be a viable alternative for ac grid interconnections, due to this, and to the novel circumstances of the VFT it is highly recommended to investigate machine further. There are several aspects of the VFT-operation that will benefit extended research. The reactive power issue requires further investigation, and different reactive power control schemes should be evaluated and optimized. Additional reactive power compensation devices should be assessed in a collaboration with the VFT to increase the power factor and overall capacity of the system. As previously mentioned, the voltage variations analyzed in this thesis was minimal, thus, it would be interesting to see the effect of larger voltage variations. It is encouraged to analyze the response of the VFT during voltage fluctuations within the acceptable range set by system operators, usually $\pm$ 5 %. Furthermore, it is recommended to expand different control schemes of the machine. This includes, for instance, the governor which adjust the power flow/torque on a droop characteristic, power oscillation damping to prevent the oscillations of the machine angle, and the power runback control.

References

[1] L. Freris and D. Infield, *Renewable Energy in Power Systems*. John Wiley & Sons, Ltd., 2008.

[2] C. Sreelakshmi and K. Pramelakumari, "Vft-statcom coordinated system for improved power transfer between asynchronous grids," *Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)*, 2016.

[3] B. Bagen, D. Jacobson, G. Lane, and H. M. Turanli, "Evaluation of the performance of back-to-back HVDC converter and variable frequency transformer for power flow control in a weak interconnection," *IEEE Power Engineering Society General Meeting, PES*, 2007.

[4] J. Marczewski, "VFT Applications Between Grid Control Areas," *2007 IEEE Power Engineering Society General Meeting*, 2007.

[5] J. Gagnon, D. Galibois, M. Granger, D. McNabb, D. Nadeau, J. Primeau, S. Fiset, E. Larsen, G. Drobniak, I. McIntyre, *et al.*, "First vft application and commissioning," *Canada Power, Toronto, Ontario, CANADA*, 2004.

[6] D. McNabb, D. Nadeau, and A. Nantel, "Transient and dynamic modeling of the new Langlois VFT asynchronous tie and validation with commissioning tests," *International Conference on Power Systems Transients (IPST'05), Montreal, Canada*, 2005.

[7] A. Merkhouf, P. Doyon, and S. Upadhyay, "Variable frequency transformer - Concept and electromagnetic design evaluation," *IEEE Transactions on Energy Conversion*, 2008.

[8] E. R. Pratico, C. Wegner, E. V. Larsen, R. J. Piwko, D. R. Wallace, and D. Kidd, "VFT Operational Overview - The Laredo Project," *IEEE Power Engineering Society General Meeting*, 2007.

[9] A. Merkhouf, S. Upadhyay, and P. Doyon, "Variable frequency transformer - an overview," *IEEE Power Engineering Society General Meeting*, 2006.

[10] D. Nadeau, "A 100-MW variable frequency transformer (VFT) on the Hydro-Quebec TransEnergie Network-the behavior during disturbance," *Power Engineering Society General Meeting, 2007.*, 2007.

[11] P. E. Marken, J. J. Marczewski, R. D'Aquila, P. Hassink, J. H. Roedel, and R. L. Bodo, "VFT - A smart transmission technology that is compatible with the existing and future grid," *2009 IEEE/PES Power Systems Conference and Exposition, PSCE 2009*, 2009.

[12] F. I. Bakhsh, M. Irshad, and M. S. Asghar, "Modeling and simulation of variable frequency transformer for power transfer in-between power system networks," *India International Conference on Power Electronics, IICPE 2010*, 2011.

[13] G. E. Energy, "Variable frequency transformers - grid inter-tie," 2004. `http://www.gegridsolutions.com/products/brochures/powerD_vtf/vft_brochure.pdf`.

[14] J. Fletcher and J. Yang, "Introduction to doubly-fed induction generator for wind power application," in *Paths to Sustainable Energy* (N. Artie, ed.), ch. 14, London, United Kingdom: IntechOpen, 2010.

[15] S. Chapman, *Electric machinery fundamentals*. McGraw-Hill Education, 5 ed., 2012.

[16] R. R. Syed, "Doubly-fed induction machine for use in mini-hydro power plats," Master's thesis, Norwegian University of Science and Technology, 8 2015.

[17] T. Lund, P. Sørensen, and J. Eek, "Reactive power capability of a wind turbine with doubly fed induction generator," *Wind Energy*, 2007.

[18] O. Anaya-Lara, D. Campos-Goana, E. Moreno-Goytia, and G. Adam, *Offshore Wind Energy Generation Control, Protection, and Integration to Electrical Systems*. John Wiley and Sons Ltd., 2014.

[19] J. Manwell, J. McGowan, and A. Rogers, *Wind energy explained, 2nd ed.* John Wiley & Sons, 2009.

[20] O. Anaya-Lara, N. Jenkins, J. Ekanayake, P. Cartwright, and M. Hughes, *Wind Energy Generation - Modelling and Control*. John Wiley and Sons Ltd., 2009.

[21] N. Mohan, *ADVANCED ELECTRIC DRIVES Analysis, Control, and Modeling Using MATLAB/Simulink®*. Hoboken, New Jersey: John Wiley & Sons, Inc., 2014.

[22] S. Muller, M. Deicke, and R. W. D. Doncker, "Doubly fed induction generator systems for wind turbines," *IEEE Industry Applications Magazine*, 2002.

[23] M. Skrunes, "Novel frequency converter for low frequency ac offshore transmission," Master's thesis, Norwegian University of Science and Technology, Trondheim, 12 2017. An optional note.

[24] B. B. Ambati, P. Kanjiya, V. Khadkikar, M. S. El Moursi, and J. L. Kirtley, "A hierarchical control strategy with fault ride-through capability for variable frequency transformer," *IEEE Transactions on Energy Conversion*, 2015.

[25] R. J. Piwko, E. V. Larsen, and C. A. Wegner, "Variable frequency transformer - a new alternative for asynchronous power transfer," *IEEE Power Engineering Society Inaugural Conference and Exposition in Africa*, 2005.

[26] P. E. Marken, J. Roedel, D. Nadeau, D. Wallace, and H. Mongeau, "VFT maintenance and operating performance," *IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century, PES*, 2008.

[27] G. E. Energy, "Variable frequency transformer™ - fact sheet," 2004. `http://www.gegridsolutions.com/products/brochures/powerD_vtf/vft_factsheet.pdf`.

[28] F. I. Bakhsh and D. K. Khatod, "Variable Frequency Transformer - State of the art review," *2013 International Conference on Energy Efficient Technologies for Sustainability*, 2013.

[29] E. R. Pratico, C. Wegner, P. E. Marken, and J. J. Marczewski, "First multi-channel VFT application - The Linden project," *IEEE PES Transmission and Distribution Conference and Exposition: Smart Solutions for a Changing World*, 2010.

[30] F. I. Bakhsh and D. K. Khatod, "Closed loop control analysis of variable frequency transformer (VFT)," *IEEE Students' Conference on Electrical, Electronics and Computer Science*, 2014.

[31] F. Bakhsh, S. Islam, and M. Siddiqui, "Modeling, analysis and simulation of vft for power flow control through asynchronous power systems," *ACEEE Int. J. on Electrical and Power Engineering*, 2011.

[32] N. Hingoranl, L. Gyugyi, and M. El-Hawary, *Understanding FACTS: Concepts and technology of flexible ac transmission systems*. John Wiley and Sons Inc.- IEEE Press, 1999.

[33] P. Hassink, V. Beauregard, R. Q'Keefe, E. Larsen, and R. Bodo, "Second & future applications of stability enhancement in ERCOT with asynchronous interconnections," *IEEE Power Engineering Society General Meeting, PES*, 2007.

[34] P. Kundur, *Power System Stability and Control*. McGraw-hill, 1994.

[35] G. Chen and X. Zhou, "Digital simulation of variable frequency transformers for asynchronous interconnection in power system," in *IEEE/PES Transmission Distribution Conference Exposition: Asia and Pacific*, 2005.

[36] J. Machowski, J. Bumby, and J. Bialek, *Power System Dynamics: Stability and Control*. Wiley, 2 ed., 2008.

[37] P. Hassink, P. Marken, R. O'Keefe, and G. Trevino, "Improving power system dynamic performance in Laredo, TX," *IEEE/PES Transmission and Distribution Conference and Exposition*, 2008.

[38] B. B. Ambati and V. Khadkikar, "Variable Frequency Transformer Configuration for Decoupled Active-Reactive Powers Transfer Control," *IEEE Transactions on Energy Conversion*, 2016.

[39] H. Amaris, M. Alonso, and C. Alvarez Ortega, *Reactive Power Management of Power Networks with Wind Generation*, vol. 5. Springer, 2013.

[40] S. Grunau and F. W. Fuchs, "Effect of Wind-Energy Power Injection into Weak Grids," *EWEA 2012 Conference Proceedings*, 2012.

[41] H. Markiewicz and A. Klajn, "Voltage Disturbances," *Power quality Application Guide*, 2004.

[42] M. Gupta, A. Martinez, and S. Saylors, "Experiences with Wind Power Plants with Low SCR," *IEEE PES General Meeting, Denver*, 2015.

[43] N. Mohan, T. Undeland, and W. Robbins, *Power Electronics. Converters, Applications and Design*. John Wiley & Sons, Inc., 3 ed., 2003.

[44] Z. Yang, C. Shen, L. Zhang, M. L. Crow, and S. Atcitty, "Integration of a statcom and battery energy storage," *IEEE Transactions on Power Systems*, 2001.

[45] M. Molinas, S. Vazquez, T. Takaku, J. Carrasco, R. Shimada, and T. Undeland, "Improvement of transient stability margin in power systems with integrated wind generation using

a STATCOM: an experimental verification," *International Conference on Future Power Systems*, 2005.

[46] E. Barrios-Martínez and C. Ángeles-Camacho, "Technical comparison of FACTS controllers in parallel connection," *Journal of Applied Research and Technology*, 2017.

[47] K. Padiyar, *HVDC Power Transmission Systems: Technology and System Interactions*. New Age International, 1990.

[48] S. Chattopadhyay, M. Mitra, and S. Sengupta, *Clarke and Park Transform*. Dordrecht: Springer Netherlands, 2011.

Appendix A

Case 3: Active power flow

A.1 Scenario 1: Weaker grid side receiving active power - compensation by capacitor bank in grid side 2

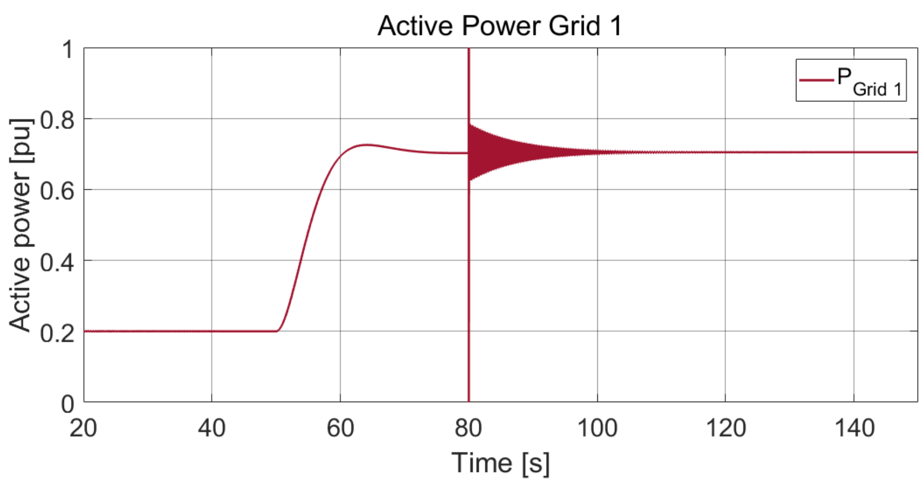

Figure A.1: Case 3, Scenario 1: Active power grid 1

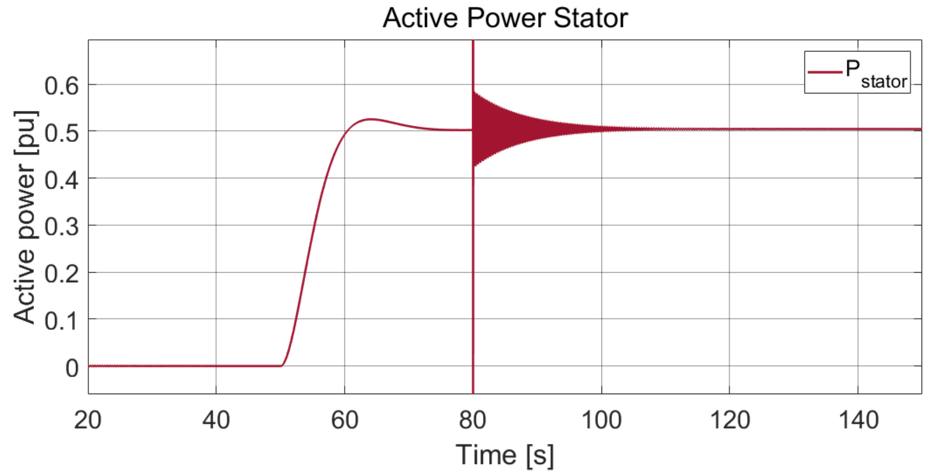

Figure A.2: Case 3, Scenario 1: Active power stator

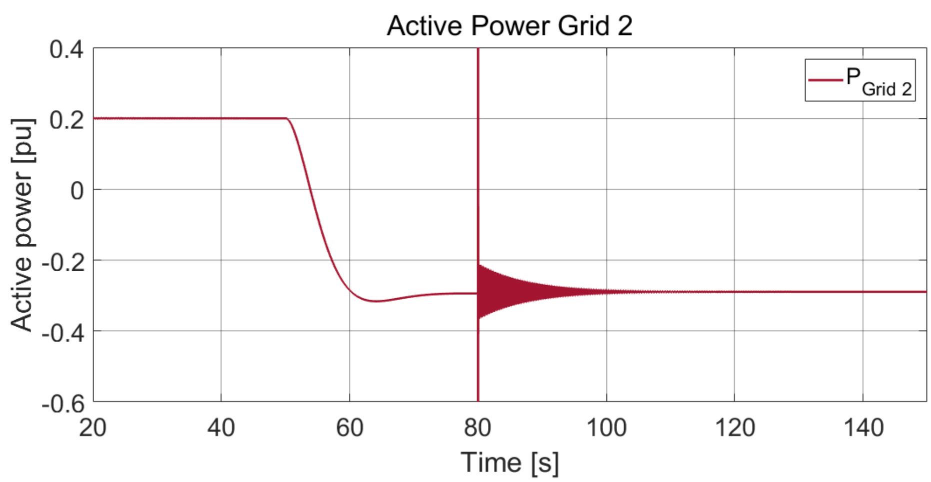

Figure A.3: Case 3, Scenario 1: Active power grid 2

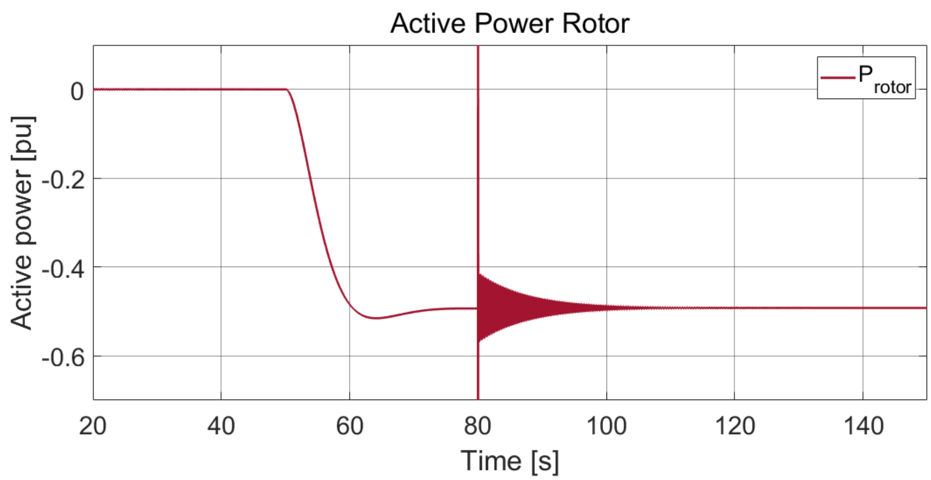

Figure A.4: Case 3, Scenario 1: Active power rotor

A.1.1 Scenario 2: Weaker grid supplying active power - compensation by capacitor bank in grid side 1

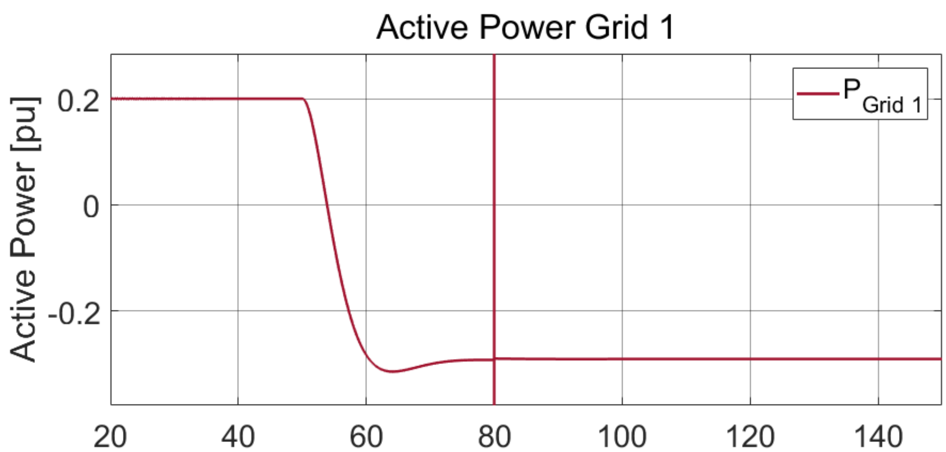

Figure A.5: Case 3, Scenario 2: Active power grid 1

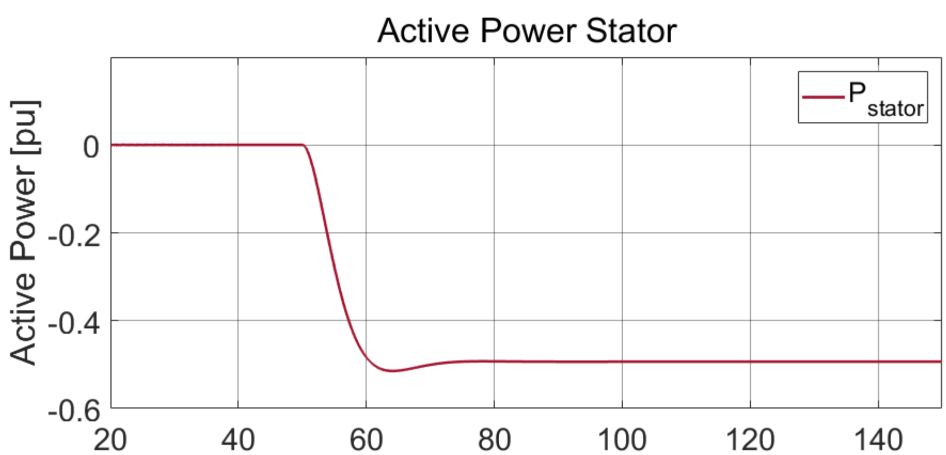

Figure A.6: Case 3, Scenario 2: Active power stator

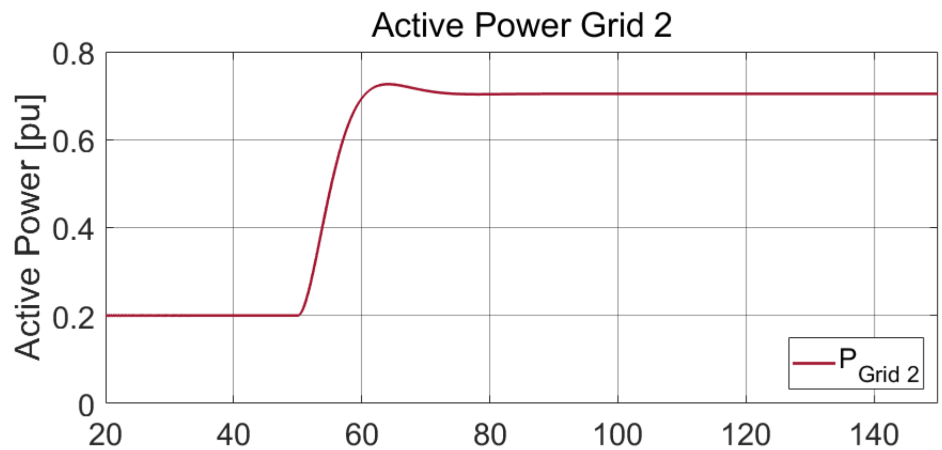

Figure A.7: Case 3, Scenario 2: Active power grid 2

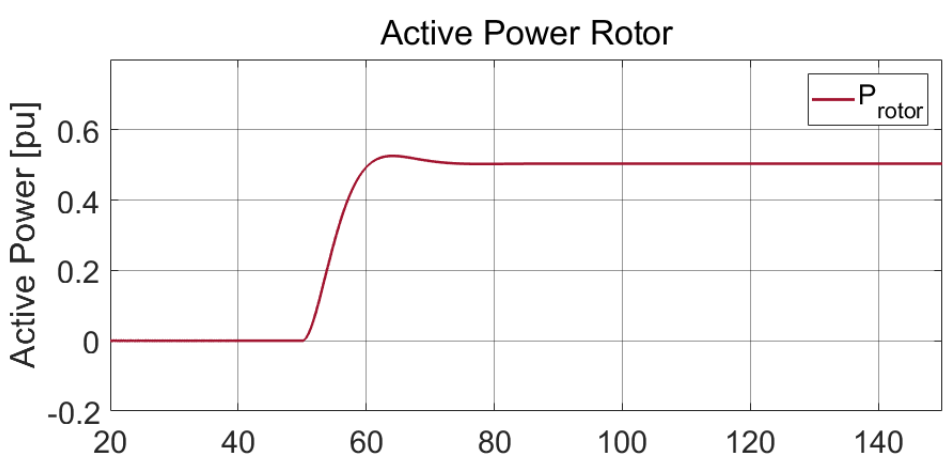

Figure A.8: Case 3, Scenario 2: Active power rotor

Appendix B

Case 4: Active power flow

B.1 Asynchronous grids, weak grid, capacitor bank

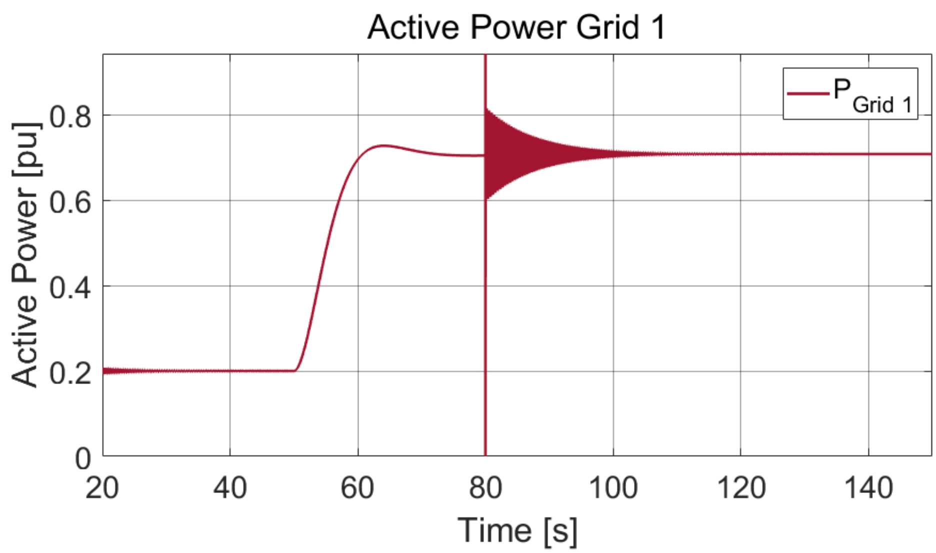

Figure B.1: Case 4: Active power grid 1

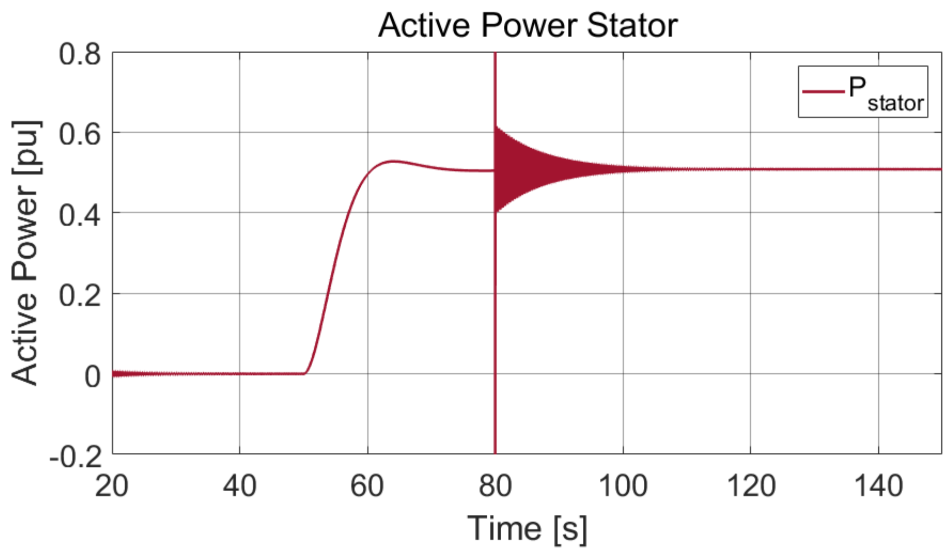

Figure B.2: Case 4: Active power stator

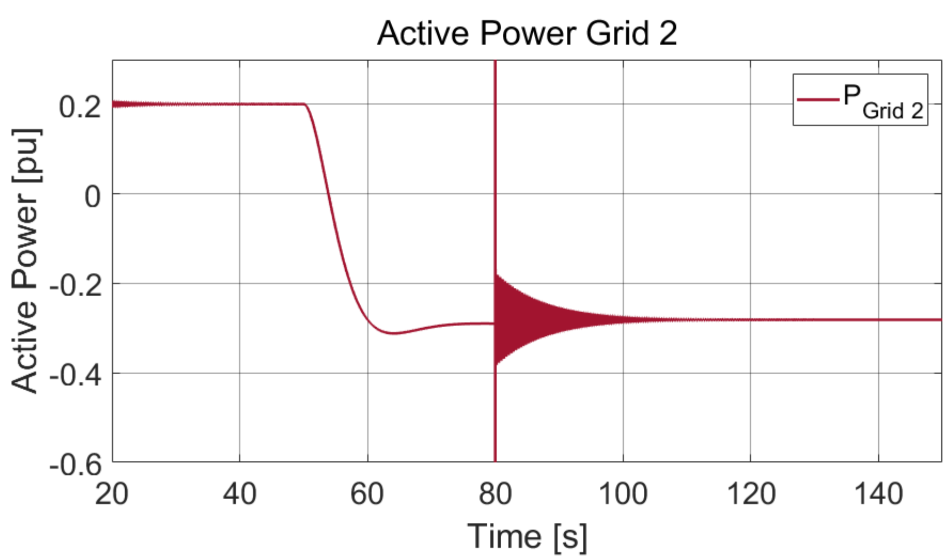

Figure B.3: Case 4: Active power grid 2

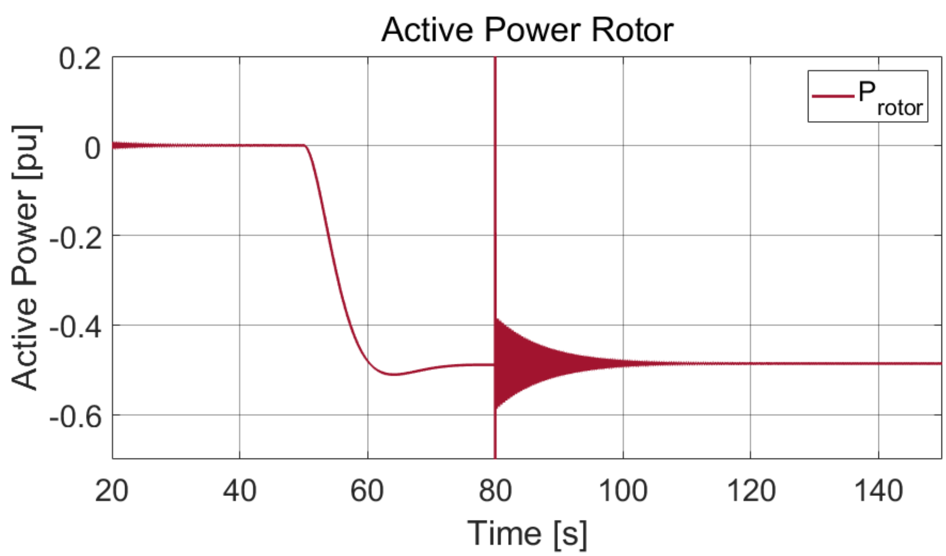

Figure B.4: Case 4: Active power rotor

Appendix C

Parks and Clarks Transformation

The most common method used for controlling VSC today is the vector control method. The vector control method is generally used to obtain independent control of active and reactive power. In the following the different steps in the control system of the STATCOM is described. The Clarke and Inverse Clarke transformation are used to convert three phase signals of voltages and currents into stationary $\alpha - \beta$ complex reference frame, and conversely. The Park and Inverse Park transformation converts the stationary $\alpha - \beta$ reference frame into rotating d-q reference frame, and vice versa. The d-q reference frame rotates at a speed ω. The transform operation presented in this chapter is based on [48].

C.1 Clarke and Inverse Clarke Transformation

To simplify the analysis the α-axis is aligned with the three-phase a-axis as shown in fig. **??**.
The Clarke transformation is as follows.

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{C.1}$$

v_0 is the zero sequence voltage. The zero sequence voltage is only non-zero when the system is unbalanced. Thus, under normal operating conditions equation C.1 becomes:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{C.2}$$

The inverse Clarke transformation is thus:

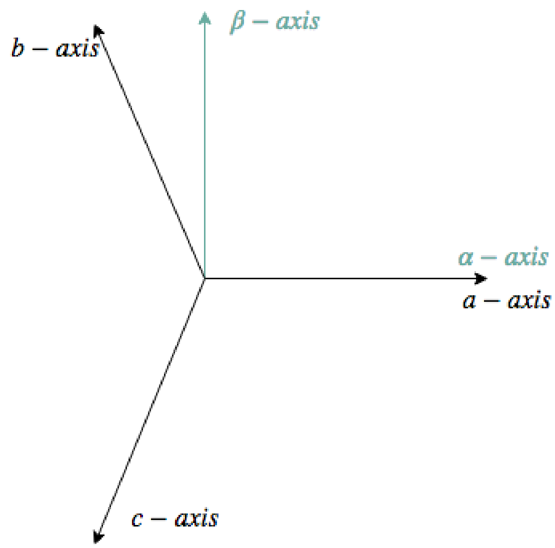

Figure C.1: Stationary, complex reference frame for Park and Clarke transformation

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{C.3}$$

C.2 Park and Inverse Park Transformation

The Park transformation matrix is given by the following equation.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{C.4}$$

The inverse Park transformation matrix is given by equation C.5

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} v_d \\ v_q \end{bmatrix} \tag{C.5}$$