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DATA COMMUNICATIONS AND APPLICATION DEVELOPMENT OF A FULL-POWER CONVERTER IN WIND POWER SYSTEMS

Master of Science Thesis

Examiner: Prof. Seppo Valkealahti
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ABSTRACT

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Wind power is a promising source for renewable, distributed energy. Although one of the most mature renewable energy technologies, it has a lot of potential for improvement, for example in terms of reliability, efficiency, and environmental impact.

This master of science thesis gives an introduction to one power converter technology commonly used in wind power systems, a full-power converter. A full-power converter is a power electronics device, which processes all the power generated by a wind turbine generator connected to it. It gives the energy producer full control over the generated power, and helps to meet the increasing national and international demands for power quality.

As a point of particular interest in the thesis are the data communications in and out of the full-power converter product of a Finnish technology company, The Switch, and the development of the product to meet the increasing demands of the industry. An introduction is given to the fieldbus technology used for local connections, and how a remote access functionality is implemented in the product using the Tosibox Lock & Key remote access system.

A simplified configuration routine for the data communication system, and an administration strategy for the connections are developed as one of the main goals of the thesis. The intention is to have a straightforward method, so that the routine can be independently executed by the company's testing personnel in any of the company's locations, and so help the company to allocate usable resources more effectively in every production phase.

The thesis continues to implement new features to the automation application of the product, as well as a new protection feature, which together supplement the final product well and give the customers more feature-rich and safe product.

TIIVISTELMÄ

TUOMAS SALOKANTO: Täystehokonvertterin tietoliikenneyhteyksien ja logiikkaohjelmiston kehitys tuulivoimasovelluksissa
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Tuulivoima on lupaava ja eräs kehittyneimmistä hajautetun uusiutuvan energian lähteistä, missä on kuitenkin paljon tilaa kehitykselle, esimerkiksi luotettavuuden, tehokkuuden, ja ympäristövaikutusten näkökulmista.

Tämä diplomityö perehdyttää lukijan erääseen yleiseen tuulivoimasovelluksissa käytettyyn tehonmuokkainteknologiaan, täystehokonvertteriin. Täystehokonvertteri on tehoelektroniikkalaite, joka käsittelee kokonaisuudessaan kaiken sen läpi kulkevan, tuulivoimageneraattorilta tulevan tehon. Se mahdollistaa tehon tuottajalle täyden kontrollin tuotettavan tehoon, ja auttaa vastaamaan kasvaviin tehonlaadun vaatimuksiin.

Erityisen mielenkiinnon kohteena työssä on suomalaisen teknologiayrityksen, The Switch Oy:n, täystehokonvertterituote ja sen tietoliikenneyhteydet, sekä tuotteen kehittäminen vastaamaan teollisuuden kasvavia vaatimuksia. Työssä perehdytään tuotteen fyysisissä paikallisyhteyksissä käytettyyn kenttäväyläteknologiaan, sekä etäyhteyksien muodostamiseen käyttäen suomalaisen Tosibox Oy:n Lukko & Avain -etäyhteysteknologiaa.

Yksi työn keskeisimmistä tavoitteista on yksinkertaistaa tuotteen tietoliikenneyhteyksien muodostamiseen käytetty konfiguraatiorutiini, ja kehittää valmiiden yhteyksien hallinnointimenetelmä. Lopullisena tavoitteena on saada suoraviivainen ja dokumentoitu metodi, jonka voi suorittaa itsenäisesti kuka tahansa yrityksen testaushenkilöstöstä, missä tahansa yrityksen kohteista. Näin yrityksen on mahdollista jakaa resurssejaan tehokkaammin eri tuotantovaiheissa.

Lopuksi työssä toteutetaan joitain uusia ominaisuuksia tuotteen logiikkaohjelmistoon, sekä uusi suojaustoiminto. Yhdessä ne tekevät viimeistellystä tuotteesta monipuolisemman ja turvallisemman asiakkaalle.

PREFACE

This master's thesis was written for The Switch Drive Systems Oy in Vaasa, alongside my daily job in the application development team.

First of all, I want to thank The Switch and my supervisor Jyrki Sorila for choosing me to the team and giving me the possibility to write this thesis, and for organizing me time to work on it in the middle of hectic schedules. Having a topic that closely relates to my everyday job helped me greatly in being able to finish the thesis almost on time. I also want to give acknowledgements to Julius Luukko and Tomi Knuutila for providing me with ideas and encouragement. Huge thanks also to professor Seppo Valkealahti for choosing to act as the examiner of my thesis, for his precious feedback, and for always finding the time to respond quickly to my inquiries.

A special commendation to my wife Justina for helping me with proof-reading and for enduring boring evenings watching me working late on the subject. Finally, I want to thank my parents for helping me choose this profession and for encouraging me through my seemingly unending journey of studies.

Vaasa, 11 November 2016

Tuomas Salokanto

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LIST OF ABBREVIATIONS AND SYMBOLS

3G	Third generation wireless mobile telecommunications technology
4G	Fourth generation wireless mobile telecommunications technology
AES	Advanced Encryption Standard
AC	Alternating Current
ADS	Automation Device Specification
ADSREAD	Function in TwinCAT for reading SDO messages
ADSWRITE	Function in TwinCAT for writing SDO messages
ARP	Address Resolution Protocol
CAN	Controller Area Network
CANopen	High-level communication protocol based on CAN
CBC	Cipher Block Chaining
CFC	Continuous Function Chart programming language
CX5010	A Programmable Logic Controller product from Beckhoff
DBU	Dynamic Braking Unit
DC	Direct Current
DC-link	Connection point of the inverter and the rectifier
DFIG	Doubly Fed Induction Generator
DHCP	Dynamic Host Configuration Protocol
dq	A reference frame with direct and quadrature axes
$\mathrm{d}v/\mathrm{d}t$	A filter type used in voltage spike control
DVI	Digital Visual Interface
EESG	Electrically Excited Synchronous Generator
EL1008	A digital input extension terminal model from Beckhoff
EL1018	A digital input extension terminal model from Beckhoff
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
EtherCAT	Ethernet for Control Automation Technology fieldbus system
FBD	Function Block Diagram programming language
FPC+	Full-Power Converter product of The Switch
GND	Ground potential
HVRT	High Voltage Ride-Through
IGBT	Insulated Gate Bipolar Transistor

I/O	Input/Output
IL	Instruction List programming language
IEC	International Electrotechnical Commission
IP	Internet Protocol
LAN	Local Area Network
LC	A filter consisting of an inductor and a capacitor
LCL	A filter consisting of an capacitor and two inductors
LD	Ladder Diagram programming language
LTspice	Circuit simulation software
LVRT	Low Voltage Ride-Through
MOSFET	Metaloxidesemiconductor Field-effect Transistor
NAT	Network Address Translation
NPN	A bipolar junction transistor type
PC	Personal Computer
PDO	Process Data Object
PKI	Public Key Infrastructure
PLC	Programmable Logic Controller
PMSG	Permanent Magnet Synchronous Generator
PoE	Power over Ethernet
PUK	Personal Unlocking Key
PWM	Pulse-Width Modulation
RMS	Root Mean Square
RPDO	Receive Process Data Object
RPM	Revolutions Per Minute
RS-422	Standardized serial connection
RSA	A public key cryptosystem used in data transmission
SCIG	Squirrel-Cage Induction Generator
SDO	Service Data Object
SFC	Sequential Function Chart programming language
SIM	Subscriber Identity Module
ST	Structured Text programming language
TCP/IP	Transmission Control Protocol/Internet Protocol suite
THD	Total Harmonic Distortion
TLS	Transport Layer Security
TPDO	Transfer Process Data Object
TwinCAT	Beckhoff's automation control software suite
USB	Universal Serial Bus

VMB	Voltage Measurement Board
VPN	Virtual Private Network
VSI	Voltage Source Inverter
WAN	Wide Area Network
WTC	Wind Turbine Controller
x86	A processor architecture

C	Capacitance
C_{DC}	Capacitance of the DC-link
f	Frequency
h	Ordinal of harmonic frequency
i_{d}	Direct axis current component in dq-reference frame
i_{q}	Quadrature axis current component in dq-reference frame
I	Current
I_{s}	Sink current of a fan's internal transistor
k	Last ordinal of harmonic frequency taken into account
L	Inductance
n	Rotation speed in RPM
P	Active power
Q	Reactive power
R	Resistance
R_{fan}	Fan's internal resistance
$R_{\mathrm{pull\text{-}up}}$	Resistance of a pull-up resistor
t	Time
$\mathrm{THD}_{\mathrm{v}}$	Total Harmonic Distortion of voltage
$\mathbf{v}$	Grid voltage space vector
v_{d}	Direct axis voltage component in dq-reference frame
v_{q}	Quadrature axis voltage component in dq-reference frame
V	Voltage
V_1	Voltage at harmonic frequency ordinal 1 (base frequency)
V_{DC}	Voltage of a DC voltage source
V_h	Voltage at harmonic frequency ordinal h
V_{n}	Nominal operating voltage of a fan
V_{r}	Residual voltage of a fan's internal transistor
V_{s}	Voltage of the tachometer output
$V_{\mathrm{s,high}}$	Voltage high level of the tachometer output
$V_{\mathrm{s,low}}$	Voltage low level of the tachometer output
ω	Angular frequency

1. INTRODUCTION

The Renewable Energy Directive of the European Union has laid a set of rules for the members of the union to achieve its target, which defines that 20 % of all energy produced should be from renewable energy sources by 2020. The exact percentage depends on the member country, and for example in Finland's case it is 38 %, the third highest requirement among all member countries. [1] New targets are already set for 2030, by when even a higher percentage of renewable energy is required [2].

The increasing demand for electrical energy from renewable energy sources brings challenges to the governments of European Union member countries and their energy producers. Producing electrical energy from renewable energy sources is still considerably more expensive in comparison to conventional sources, mostly because of more immature technologies. The manufacturers are constantly developing their products in many ways to better meet the increasing demands. Wind power is one of the most advanced and researched technologies for renewable energy production. While considered mature, it still has much room for improvement in the future in terms of energy efficiency, reliability, and environmental impact.

In the era of the Smart Grids and the Internet of Things, remote connectivity has become a rising technology trend. Almost everything can be integrated into a network of interconnected devices which communicate with each other, collect data from their environment and optimize their operation accordingly. Setting up a remote monitoring and control system for an establishment such as a wind power plant is not a trivial task. Harsh operating conditions and considerable electromagnetic interference caused by the generation of megawatts of power raises many challenges, as well as the attention that must be given to network security.

In this master's thesis, the local and remote connectivity possibilities of a full-power converter used in wind power applications are discussed. At the heart of the study is a full-power converter product, FPC+, from a Finnish technology company The Switch. A simplified communication device configuration routine and an administration system for the connections are developed for more cost-efficient and straightforward set-up. The automation application of the cabinet is developed to support new functionalities and to improve data communications and product reliability, making the product more competitive and complete.

In the second chapter, the background of different generator systems and the theory of a full-power converter used in wind power applications are explained in needed detail, what will help the reader to understand the motivation and benefits over other competitive systems. A brief introduction is given to the full-power converter product, the FPC+, to give the reader a complete picture of the converter system in the center of this thesis. In the third chapter, the fundamentals of local and remote connectivity of the FPC+ and possible challenges, such as information security and electromagnetic interference, are discussed. Fieldbus protocols and hardware components used for data communications are presented, and their benefits explained.

In the fourth chapter, a configuration routine for all the included communication devices is created and documented for a faster and more cost-beneficial set-up during the mass production phase. With the revamped procedure, the configuration can be straightforwardly performed by any employee without the need for development team intervention. Administration practices for remote connections are developed to be able to keep track of all the information stored during the set-up. A database is created to store all the data gathered during the configuration to be able to keep track of all converter cabinets of all customers.

In the fifth chapter, two product development tasks are carried out for the FPC+. Parameter exchange between the cabinet automation control and the primary controls is developed to allow the customer to access chosen parameters, concerning for example the cabinet temperature limits, and to change them within set limit values. This way the customers can themselves modify some of the automation control parameters, in addition to the already accessible operational parameters of the primary controls, without the need for application modifications by The Switch. A condition monitoring functionality is implemented for the power module cooling fans, to notify the customer about possible malfunctioning in the fans, and allowing them to act in time before the fault affects the lifetime of any critical components.

The sixth chapter finally summarizes the core findings of the thesis.

2. FULL-POWER CONVERTER IN WIND POWER SYSTEMS

A power electronics converter is a device that acts as an interface between the electrical grid and the generator of a wind turbine. It modifies the electricity generated by the generator from the kinetic energy of the wind to a steady AC (Alternating Current) waveform with the frequency required by the grid, typically 50 Hz or 60 Hz. This is needed with variable speed synchronous generators, because the output voltage's amplitude and frequency are dependent on the rotation speed of the generator, and thus on wind speed. Supplying voltage whose amplitude and frequency deviate considerably from the nominal values of the grid will cause problems for its stability and for everything connected to it. The speed of the wind cannot be controlled, but the amplitude and frequency of the output voltage can, with the help of a power electronics converter.

A full-power converter is a type of power electronics converter that handles all the power that is generated by the wind turbine before supplying it to the grid. This has some clear benefits especially for wind power applications, for example the complete control over the power factor, and easier fulfilling of grid compliance requirements for flicker and fault ride-through. Another popular type used in industry is the DFIG (Doubly Fed Induction Generator) based converter topology, which handles only about one third of the generated power, while the rest is fed directly from the generator stator to the grid as it is. As a result, the converter can be manufactured considerably smaller in volume and with decreased costs, but with less control over the generated power.

In this chapter, a brief introduction is given to the different generator types commonly used in wind power systems, aiming to motivate the use of permanent magnet synchronous generators. The inner structure and benefits of a full-power converter are explained in detail, and how they work well in synergy with permanent magnet synchronous generators in wind power applications. Finally, an introduction is given to the new full-power converter product of The Switch, the FPC+, as it is in the center of this master's thesis.

2.1 Generator concepts in wind power systems

Wind power systems come with plenty of different designs to fit different needs. They can be classified for example by the rotating axis alignment, the type of the generator, or the rotation speed. Few of the most common technologies include the fixed speed SCIG (Squirrel Cage Induction Generator), the variable speed DFIG, the EESG (Electronically Excited Synchronous Generator), and the PMSG (Permanent Magnet Synchronous Generator). Their introduction is given shortly in this section.

2.1.1 Squirrel-cage induction generator

The SCIG is traditionally used in an upwind, stall-regulated wind turbine concept, popularized by the Danish in the 1990s. It operates in a very narrow speed range around its synchronous speed and is for that reason called a fixed speed generator. It is directly connected to the grid with a transformer, and needs a multi-stage gearbox to achieve high enough rotation speed for the shaft, as the wind turbine's rotor speed is much lower than needed for optimal electrical operation of the generator. The SCIGs are robust in structure, easy to use, and cheap to produce, but lack many features that are generally desired in modern wind power systems. Most of the problems are related to its fixed speed nature that prevents the control of the rotation speed. This means that the turbine's speed cannot be optimized for the best possible aerodynamic efficiency, and power generation is only possible at wind speeds high enough to rotate the shaft faster than the generator's synchronous speed. Wind speed fluctuations are also directly transmitted into electromechanical torque vibrations, which causes mechanical stress to the system. [3]

2.1.2 Doubly fed induction generator

The DFIG concept consists of a wound rotor induction generator and a partial-scale power electronic converter. The stator of the DFIG is directly connected to the grid while the rotor is connected via the converter. Typically, the power rating of the used converter is around 30 % of the generator's capacity, what makes it an affordable solution. It enables reactive power compensation and smoother grid connection and gives control over the rotation speed, typically approximately ±30 % around the synchronous speed. For the same reasons as for the SCIG, it also requires a multi-stage gearbox which has its drawbacks. Also a slip ring is needed to transfer power from the rotor to the converter. It needs regular maintenance and may cause failures in operation if it malfunctions. In case of a fault in the grid, the large stator currents in the DFIG are transferred to the rotor current, so the partial-scale converter needs to be protected against much higher currents in comparison to full-power converters. [3]

2.1.3 Synchronous generators

Synchronous generators do not depend on induction to excite and rotate the rotor. Thus, they do not require slip to produce power, and rotate precisely at the set speed. The EESG, as the name suggests, uses electrically excited rotor windings as electromagnets to produce the rotating force in cooperation with the three-phase AC fed stator windings. They need to be accompanied with a full-power converter, allowing full control over the amplitude and frequency of the output voltage at a very wide rotation speed range, but also increasing the total cost of the system. As the rotor is electrically excited with DC (Direct Current), slip rings or similar devices must be used to supply the power to the rotor. The PMSG is similar in structure to EESG, except for the rotor, which is constructed of permanent magnets. This removes the need for slip rings and similar mechanical devices, because an additional power supply for generating the magnetic field is no longer required. This improves the longevity and reliability of the generator and removes the source for excitation losses. Both EESG and PMSG can be manufactured to be direct-driven or with a gearbox. [3] [4]

Synchronous generators based on permanent magnets provide many benefits in wind power use. PMSGs have in general higher efficiency and they provide higher overall energy yield, especially in the partial load operational ranges, in other words, with lower wind speeds. The rare earth magnets are lighter than the wound electromagnets, which leads to higher power to weight ratio, what is important especially when the wind turbine power ratings get higher and higher [5]. On the downside, the rare earth metals used in the manufacturing of the magnets are costly, although decreasing, and represent a large fraction of the total cost of the generator. [6]

In multimegawatt-class wind power systems, one of the increasingly common choices for a turbine has become a horizontal-axis PMSG design, due to its light weight, small volume, and reliability [7]. It is also the design that The Switch uses in its wind turbine generators, so this technology is chosen for further examination in this thesis. At the moment of writing, the most powerful permanent magnet wind turbine generator in the world is a 8.6 MW medium-speed generator, currently in production by The Switch.

2.2 Structure of a full-power converter

In this section, the general structure of a typical full-power converter is introduced. The main parts of interest are the semiconductor switching device modules handling the actual power conversion, grid filters used for enhancing the power fed to the grid and to minimize harmonics, and the primary control electronics and other auxiliary devices. Full-power converters exist in many topologies and for multiple purposes, but it is not worthwhile to go through all of them in the scope of this thesis. The examination is thus limited to a two-level back-to-back connected converter, a typical choice for a wind turbine system. The structure and inner workings of this topology are explained in this section.

2.2.1 Power electronics

The heart of the converter is the IGBT (Insulated Gate Bipolar Transistor) modules. IGBTs have become a popular choice for a semiconductor switching device in megawatt-class power converters, mainly because they are thoroughly researched and widely used in industry, and as such easily available. They are also easily controlled with a voltage signal and can handle very high currents. IGBTs work well in parallel because of their positive temperature coefficient, which is necessary when even higher current handling capacity is required [8, p. 158]. On the downside, they have higher switching losses in comparison for example with MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistor), but this is not a critical issue in wind power converters where this high switching frequency is not necessary.

Many different topologies for the power electronics exist for different purposes, depending on what kind of output is required. One popular power electronics topology for a megawatt-class wind power converter is the two-level back-to-back connected voltage-source inverter topology, which is presented here. It consists of two VSIs (Voltage Source Inverter) interconnected back-to-back together from their DC-sides. Both VSIs are composed of six IGBTs acting as power switches. The term two-level refers to the number of different voltage potentials implemented in the output voltage, in this case two, the positive and the negative potential. [9, p. 712] The fundamental layout of this converter topology is presented in Figure 2.1.

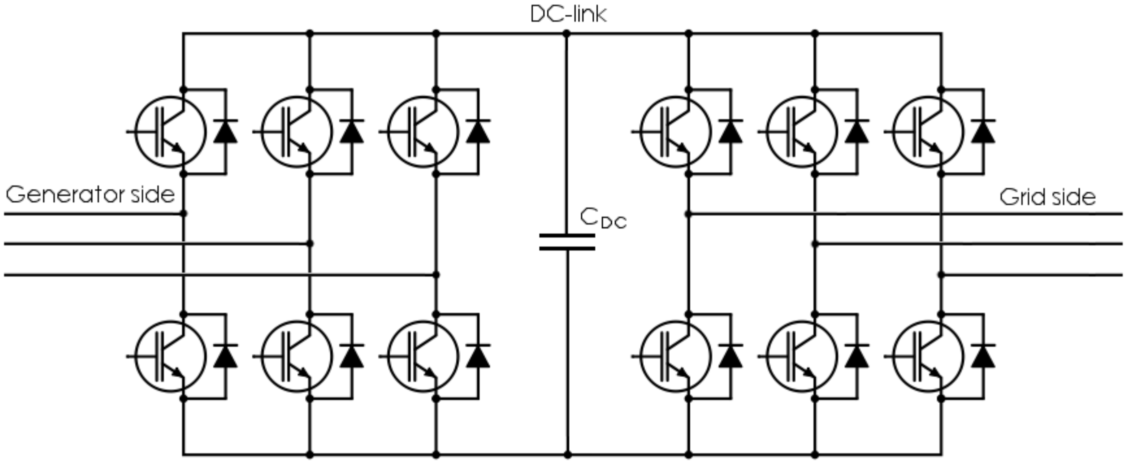

Figure 2.1 *The fundamental layout of the IGBT modules in a back-to-back connected converter.*

In Figure 2.1 three main parts are specified: The grid side inverter, the generator side inverter, and the DC-link in between them. During normal operation, when the wind turbine generator feeds power to the grid, the generator side inverter works as a rectifier bridge, and the grid side inverter as an inverter. The grid side inverter is commonly called the active front end, because its operation is actively controlled utilizing active switching components, the IGBTs, in contrast to a non-controlled unidirectional inverter consisting of passive switching components such as diodes. Active control enables bidirectional current flow by changing the switching sequence of the IGBTs and by making use of the antiparallel diodes. [10] An active front end also provides means for power factor alteration by allowing free control of the reactive power by controlling the direct and quadrature components of the output current [11, p. 132].

The area where the two DC-sides of the inverters are connected together is called the DC-link. The capacitance C_{DC} in the DC-link illustrated in Figure 2.1 functions as a temporary energy storage during power conversion and stabilizes the voltage transients of the DC-link. A pre-charge circuit is used to charge the DC-link capacitor before the converter is connected to the grid. This is done to protect vulnerable components such as the diode bridge and the DC-link capacitors from a current rush during start-ups immediately after the circuit breakers are closed.

The basic operation principle of the converter is simple. The generator side inverter unit controls the generator torque and rectifies the AC generated to the terminals of the generator and feeds it to the DC-link. The grid side inverter controls the DC-link voltage level and inverts the DC back to AC, and with the help of the grid filters produces a stable voltage with wanted amplitude and frequency so that it matches the utility grid regulations. [9, p. 709] The rectifying and inverting happen by switching the IGBTs on and off with a precise low voltage pulse sequence instructed by a control algorithm programmed in the primary control units, which will be introduced in Section 2.2.3. The IGBT is said to be on when the gate-emitter voltage V_{GE} of the transistor is positive, and it is in a conductive state. Correspondingly, the IGBT is off when V_{GE} is either negative or zero, depending on transistor design. [12, p. 629] A particularly common method for controlling the on and off states of the IGBTs is the PWM (Pulse-Width Modulation) scheme, where the wanted output waveform is generated by precisely determining the on and off times of the IGBTs. Both, the AC/DC and DC/AC conversion, can be achieved with pulse-width modulation. [12, p. 203]

A DBU (Dynamic Braking Unit) is an active switching device with a controller that is used to redirect power to an external resistor if the DC-link voltage exceeds its limit, for example during system disturbances, faults, or generator braking. A dynamic brake is commonly used instead of a passive chopper circuit.

Power flow to the opposite direction is also possible, where the power from the grid is used to feed the generator running it as a motor, but such situation happens rarely in wind power applications. Such functionality is needed for example during commissioning where the generator is run as a motor for the positioning of the blades, but not during normal operation. A power converter that enables an electrical machine to be run in both directions and to be used as a generator in either direction, is called a four-quadrant converter. [12, p. 122]

2.2.2 Filtering

In addition to the power conversion, filtering is an essential part of the functionality of a full-power converter. Filtering is used on both sides of the converter to achieve a good voltage quality. The quality of the voltage is defined by how much it deviates from the nominal characteristics. These deviations can be caused by many different mechanisms, for example by transient overvoltages, voltage dips, flicker, and most importantly harmonics in case of three-phase systems. On generator side filtering is used to soothe the generator waveforms, protecting its winding insulation from high voltage spikes which would lead to early aging and degrading [14, p. 681]. Filtering is needed also on the grid side before it is supplied to the utility grid, to ensure its quality and compatibility with the grid requirements [15, p. 1644].

On the generator side, the filtering can be accomplished in various ways. One typical solution is a so-called $\mathrm{d}v/\mathrm{d}t$-filter which, as the name with a time derivative suggests, works by slowing down the rate of change of the voltage v with respect to time t. The filter is constructed from inductors and capacitors in a low-pass arrangement, with the inductance and capacitance values calculated to fit the application in question. [14, p. 681]

On the grid side, the filtering is not fundamentally much different in comparison with the generator side in terms of used hardware components, though the objective is different. The main targets for grid side filter design are minimizing the THD (Total Harmonic Distortion) of the output current while minimizing power losses caused by the filter itself. The type of the filter on the grid side is typically a LC or a LCL filter, depending on the customer's needs. In the filter's name, the notation L refers to inductance, and C to capacitance. A simple L filter, consisting only of an inductor, does not provide enough harmonics attenuation without a massive physical structure if the used switching frequency is not high enough. [13, p. 2122] The choice between a LC and a LCL, or any other filter, is a compromise between parameters such as efficiency, weight and volume.

In addition to a L filter's inductor, a LC filter has extra capacitors to provide damping for voltage spikes. The principle of a LC filter in relation to the converter and the grid is shown in Figure 2.2. A LC filter usually provides enough harmonics attenuation for typical switching frequencies used in full-power converters in wind power systems, while still maintaining a relatively compact structure.

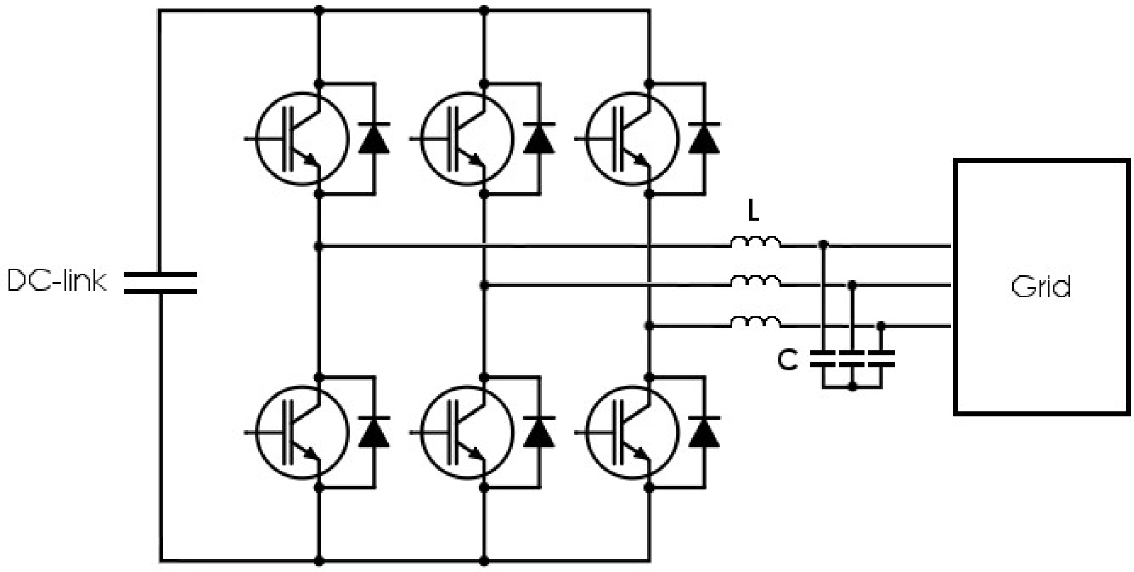

Figure 2.2 *Principal structure of a three-phase LC filter commonly used in grid side filtering of a full-power converter.*

A LCL filter adds a second inductor per phase to the circuit, providing even higher attenuation and lower current ripple across the grid inductor in comparison to LC. However, the more complex the filter structure is, the more complex its control becomes. On that account, the suitable filtering structure has to be decided individually for each system. [15, pp. 1644–1645]

2.2.3 Control and automation electronics

Additionally, a working power converter needs electronics and software to handle the control over the conversion tasks and to take care of the automation and communications of the whole system. The set of electronics and software taking care of the control over every aspect of power conversion and power module protection are henceforth referred to as the primary controls, whereas the electronics and software handling the communications, automation, operation sequences, and measurements are referred to as the cabinet automation. A division into two separate physical electronics is not necessary, but it is a common approach.

The primary controls are directly connected to the interfaces of the power modules using fast communications, such as optical fiber or parallel communications, to be able to receive data from the power modules and control the conversion as fast and accurately as possible.

The cabinet automation is typically handled by a separate PLC (Programmable Logic Controller), which is suitable for performing logical operations and measurements, such as cabinet temperature and humidity measurements. PLCs can typically send and receive both analog and digital signals, what makes it suitable for such functions. Multiple choices for communication interfaces are available readily, such as industrial fieldbuses and Ethernet. PLCs can be programmed with a standardized set of programming languages with a lot of documentation available.

2.3 Power quality and grid compatibility

As the penetration of wind power increases, more and more attention must be given to the power control and grid compatibility. Historically, wind turbine generators used to be directly connected to the grid, resulting in all the power pulsations caused by variation in wind speed being almost directly transferred to the grid. Also the reactive power control is very limited. Doubly fed systems, where a part of the power generated by the wind turbine is fed to the grid through a power electronics converter, were later introduced to tackle this issue providing more control over the power fed to the grid, while still being an affordable design. [9]

According to the statistics of Global Wind Energy Council, a total of over 432 GW of wind energy capacity was installed in the world at the end of 2015, steadily increasing every year. [16] As a result, even more control is required and an increasing number of countries are starting to pay attention to the grid compatibility, and tightening the demands. A full-power converter is a design targeted to fulfill these grid compatibility regulations and control issues with the help of modern power electronics.

Connecting multimegawatt power systems to the grid asks for close examination of its impact on the grid. It is common that grid codes internationally set tight rules for the power quality of the devices connected to the grid. Devices that do not satisfy the requirements are not allowed in the grid, so it is a crucial functionality for the commercial success of the device.

Second edition of the IEC's (International Electrotechnical Commission) international standard IEC 61400-21 sets the framework for the power quality characteristics of the grid connected wind turbines. It introduces characteristic parameters to be monitored and reported, such as active and reactive power characteristics and control, flicker, harmonic distortion, response to voltage drops, and grid reconnection time, as well as test procedures to test these parameters. [17]

Full-power converters provide superb grid compatibility for wind turbine systems and are in a central role in fulfilling the requirements set by the grid codes. This is because all the generated power is directed to the grid through the converter, and the conversion is fully controllable, with its own dedicated control schemes on the grid side as well as on the generator side. This induces many valuable functionalities for a full-power converter.

2.3.1 Active and reactive power control

Although reactive power is controllable to some extent in partial-scale power converters too, full-power converters can fully control the reactive current component. Full-power converters pass through the generated power in its entirety, a fact that enables the full control over the generated power. [18, p. 585] As mentioned earlier, the grid side inverter is in control of the grid voltage and the regulation of the DC-link. The grid side inverter is also responsible for keeping the converter operating with the wanted power factor, that is, the ratio of the active and apparent powers.

One method to achieve control over the active and reactive power is to transform the 3-phase AC quantities into DC quantities in a rotating dq reference frame. The DC components in the dq reference frame are called the direct, quadrature and zero components. For balanced systems, the zero-component is zero. This results in having only two DC components, the direct and quadrature, which simplifies calculations. [19, p. 94]

Active and reactive power are independently controlled with their own vector control loops by manipulating the direct axis current i_d and quadrature axis current i_q, and keeping the reference frame of the vector control scheme synchronized with the grid voltage vector. The active power is regulated by controlling the i_d current component and the reactive power fed to the grid is regulated by controlling the i_q current component. The grid voltage space vector $\mathbf{v}$ is presented in the the dq reference frame as

$$\mathbf{v} = v_\mathrm{d} + v_\mathrm{q}, \tag{2.1}$$

where v_d is the direct axis grid voltage component and v_q the quadrature axis grid voltage component. The active and reactive power, P and Q, respectively, can be then expressed in the dq reference frame as

$$\begin{aligned} P &= \frac{3}{2}(v_\mathrm{d} i_\mathrm{d} + v_\mathrm{q} i_\mathrm{q}) \\ Q &= \frac{3}{2}(v_\mathrm{d} i_\mathrm{q} - v_\mathrm{q} i_\mathrm{d}) \end{aligned} . \tag{2.2}$$

The direct axis of the reference frame is chosen to be aligned with the grid voltage, so the v_q component in Equation 2.1 is reduced to zero and the grid voltage space vector becomes

$$\mathbf{v} = v_\mathrm{d} + j0. \tag{2.3}$$

Then the active and reactive power can be expressed as

$$\begin{aligned} P &= \frac{3}{2} v_\mathrm{d} i_\mathrm{d} \\ Q &= -\frac{3}{2} v_\mathrm{d} i_\mathrm{q} \end{aligned} , \tag{2.4}$$

where v_d is equal to the amplitude of the grid voltage and in other words, constant by design. From this is evident that the active and reactive powers can both be controlled independently by manipulating the decoupled i_d and i_q currents. [19, p. 96]

Normally, the full control of the reactive power is exploited to keep the power factor as close to a unity as possible by keeping the reactive power at minimum. However, it is sometimes beneficial to increase the reactive portion of the power. This is done for example in flicker mitigation and fault ride-through situations, which will be introduced in the upcoming sections. It is also used for on-demand reactive power support for the grid, to compensate for imbalance of the grid voltage level at the connection point. With the help of a full-power converter, the voltage level of the grid can be supported to a higher degree and it can recover from imbalance faster [18, p. 587].

2.3.2 Flicker mitigation

The flicker is the human perception of grid voltage deviations causing lighting loads to visibly change their illumination intensity. These deviations in the grid voltage can be caused for example by the wind turbines feeding it with varying rates because of variations in the wind speed and the effects of the tower shadow, which periodically causes the generator output voltage to drop. For a three-bladed turbine, this happens three times per revolution. Flicker prevention is especially important in weak grids, or grids with a lot of intermittent energy sources feeding it. Small fluctuations are usually filtered by the DC-link, which is an important functionality for flicker prevention. A full-power converter's capability to provide reactive power support is another important factor in flicker mitigation. By feeding reactive power to the grid during voltage drops, the grid voltage level can be maintained as stable as possible. [22]

2.3.3 Grid fault ride-through

The wind turbine power converter's ability to survive voltage dips of specific duration where the grid voltage suddenly collapses to a very low level, even to 0 % of the nominal in all phases simultaneously, is called the LVRT (Low Voltage Ride-Through). [23] In contrast, the HVRT (High Voltage Ride-Through) means the capability to tolerate grid voltage levels temporarily exceeding the specifications for continuous use. During the grid voltage drop, the wind turbine must remain in operation for a specified duration and support the grid by injecting reactive power into it. The required duration depends on the system's nominal voltage level and the amount of reactive current injection depends on the system's rated current and the percentual voltage drop in relation to the nominal voltage. Different countries have different grid codes that determines the limits. In Figure 2.3 is presented the LVRT requirements for the Nordic grid, based on the Nordic grid code followed by Denmark, Finland, Norway and Sweden [24, p. 176].

On the y-axis of Figure 2.3 is the voltage of the grid during the fault as percentages of the nominal voltage. On x-axis is the duration of the fault in seconds. The line drawn in the figure depicts the limit above which the wind turbines are not allowed to disconnect from the grid during a grid voltage drop for the time shown in the x-axis and for the voltage drop amount shown in y-axis. For example in the Nordic

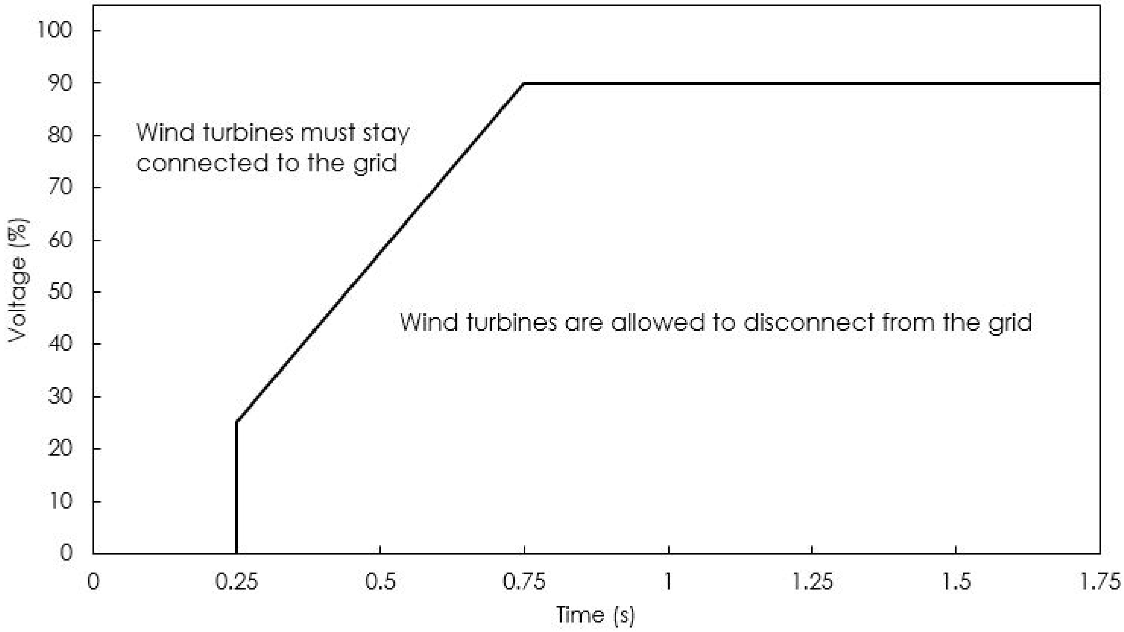

Figure 2.3 *Example diagram of the LVRT limits for the allowed grid voltage level as a function of the voltage drop time as set in the Nordic grid code.*

grid code, the wind turbines must be able to ride through a complete voltage loss for 250 ms. If the time limit for the corresponding voltage level is exceeded, the wind turbines are allowed to disconnect from the grid.

The LVRT functionality is implemented using the DBU presented in Section 2.2.1. During the grid fault, the DC-link voltage is kept stable and the generated power is temporarily directed to the brake resistor by the DBU. The resistor has very limited capacity to store thermal energy, which fundamentally limits the duration of the LVRT event it can handle. For example, a brake resistor with a thermal capacity of 5 MJ could handle a five second LVRT event at 1 MW power level. If the grid fault lasts too long and the thermal capacity is exceeded, the system has to be disconnected completely. [25] During very short voltage drops or with lower power, the LVRT can be cleared only with reactive current injection, without the need for DBU activation [23].

2.3.4 Low harmonic distortion

Grid-connected variable-speed wind turbines are an additional source for harmonic distortion for the grid, and as such they are an instability factor that needs to be addressed. Harmonics are sinusoidal voltages and currents whose frequency is an integer multiplication of the base frequency, usually 50 Hz or 60 Hz. They are caused by the non-linear nature of the power electronics converter feeding the grid. Harmonic voltages cause increased dielectric stress in electrical equipment, flicker, and may cause pulsating torques in generators. Harmonic currents cause EMI (Electromagnetic Interference) in communication network, inaccuracy in measurement instruments, and overheating and losses in cables, capacitor banks, generators, transformers and electrical devices of other kind. This leads to accelerated aging and increased costs, which is why harmonics must be quantified and addressed. [20, p. 739]

The cumulative harmonic distortion caused by the system is quantified by the THD. It can be calculated for both voltage and current harmonics using similar formula. The THD of voltage can be calculated from the ratio of the effective harmonic voltage and the system base voltage, commonly presented in percentages, using equation [12, p. 42]

$$\mathrm{THD_v} = 100\frac{\sqrt{\sum_{h=2}^{k} V_h^2}}{V_1}, \tag{2.5}$$

where $\mathrm{THD_v}$ is the total harmonic distortion of voltage, V_h is the RMS (Root Mean Square) voltage level at the harmonic frequency of ordinal h, starting from $h = 2$, and k is limited to the last ordinal of interest, around $k = 50$, as an infinite number of harmonics cannot be measured. V_1 is the RMS voltage at the system base frequency, $h = 1$. The harmonic amplitudes tend to decrease as the ordinal increases, so limiting the k for practical calculations is justified. The THD of current can be calculated by applying the Equation 2.5 and substituting the voltage components with current components.

It is generally advised to maintain the $\mathrm{THD_v}$ under 5 %, but the requirements may differ. [21] For example, a percentual $\mathrm{THD_v}$ index of 3 % for a grid-connected device is set as a recommended planning level by the Nordic grid code in Finland [24, p.

159]. Different grid codes for different countries have different requirements, and the planning premise for the THD has to be chosen accordingly. Limits can be set also for individual harmonics, not only for the total harmonics.

2.3.5 Efficiency

When compared with a partial-power converter used in DFIG set-ups, a full-power converter naturally introduces more electrical conversion losses due to the added amount of switching devices. Its advanced control possibilities on the other hand help to reach very good total system efficiency.

The control of the power converter is in an important role in tracking the maximum power point and keeping the system operating at optimal power. Losses depend on the load level and need to be identified and minimized accordingly. On the generator side control, the stator quadrature axis current component i_{q} is used to control generator's torque. The stator direct axis current component i_{d} is used for reactive power exchange between the grid side. When i_{d} is set to zero, current for the given torque is minimized, which in return keeps the ohmic losses in minimum. The value of i_{d} is also related to the stator flux, and its value affects the losses in the core. [11, p. 131]

2.4 Introduction of the FPC+ converter

The FPC+ is a product family of new generation full-power converters introduced by The Switch. It is purpose-built for distributed energy production applications, such as wind power systems, which use permanent magnet or induction machines. Most importantly, special attention is given to fulfilling the grid code requirements for harmonics, flicker, and fault ride-through, while providing a solid overall system efficiency and reliability in harsh environmental conditions. It is built to withstand high operating temperatures, making it possible to be used in areas with high ambient temperatures around the year, without wasting excessive amounts of energy for a cooling system. [27] The internal design of the converter is depicted in Figure 2.4.

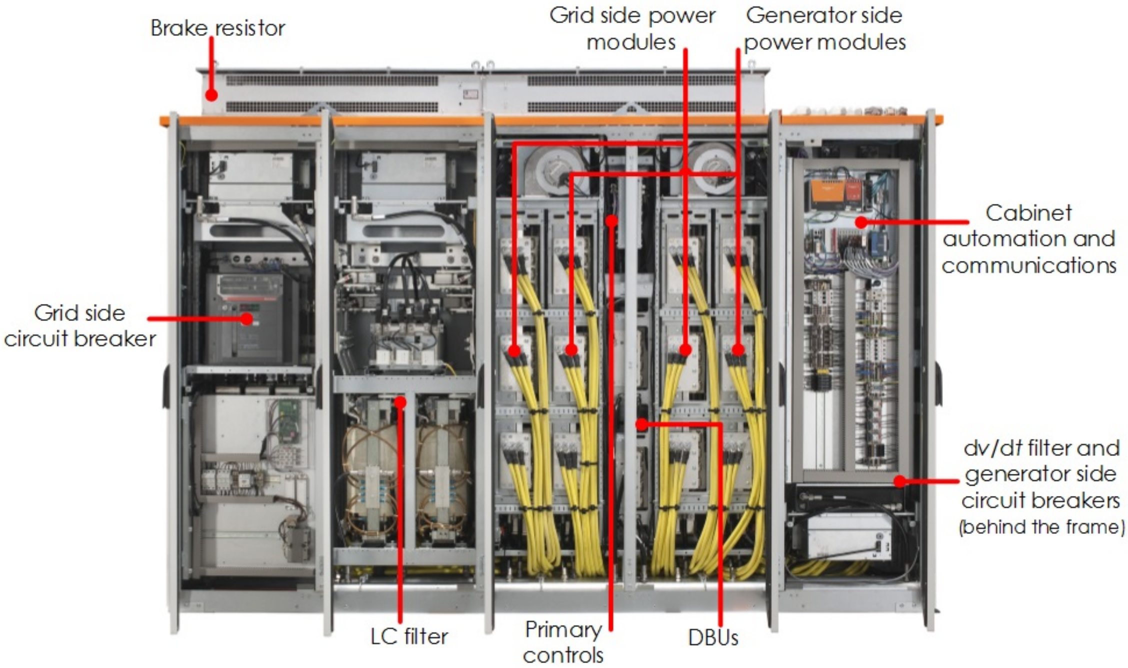

Figure 2.4 *Interiors and the main circuit parts of the FPC+ full-power converter product illustrated.*

The power conversion happens in the middle section of the cabinet, referenced in the picture as the grid side and the generator side power modules. The power modules are built from 3-phase IGBT stacks and are installed in an alternating configuration as recommended by the manufacturer, with two modules per side as illustrated in Figure 2.4. In addition to the power conversion, two extra modules are used as dynamic brake units, located in between the conversion power modules. The primary controls are located in between the conversion power modules, on top of the brake units. Auxiliary devices, such as a DC power supply, cabinet automation PLC, and communication devices, are located on a turning frame on the right side of the picture in the Figure 2.4. Behind the turning frame are the dv/dt filter and the generator side connections and breakers. The brake resistor used in conjunction with the DBU is located on top of the cabinet.

The primary controls consist of one or two control units. Normally, dedicated control electronics are reserved for both the grid and the generator side units with their own system software, but it is possible to combine them in one unit if needed. DBU control is integrated in the grid side inverter's controls. The primary controls encapsulate the control electronics, control software, and the drive control algorithms, all developed by The Switch. The primary controls are designed for distributed power generation and renewable energy systems, with modular and optimized number of automotive grade hardware components designed for wide temperature range to provide stable use in harsh environments. [28]

The control electronics consist of a control board, interface board, and a VMB (Voltage Measurement Board). The control board consists of a commercial microcontroller, a field-programmable gate array, an external watchdog processor, a real-time clock, an analog-to-digital conversion chip, and an electrically erasable programmable read-only memory, together with I/O (Input/Output) interfaces for CAN (Controller Area Network) fieldbus connection, serial connection, and other needed connections. Together they are responsible for the modulation scheme control, primary protection mechanisms, VMB control, watchdog monitoring and the internal communications. Communication to the power modules goes through the interface board, which is separate from the control board for modularity. The VMB is an external board located near the grid connection, and is responsible for the accurate sampling of the mains voltage. [28]

Multiple cabinets can be installed electrically in parallel to achieve higher powers. Up to 7.5 MW power ratings can be reached with different configurations of the FPC+ cabinets. The primary controls in this case handle the synchronization between the units, while the cabinet automation PLC can be configured to control the automation of each cabinet utilizing remote I/O terminals, without the need for multiple PLCs.

The cabinet automation control and the networking devices, located on the turning frame, are used for handling the communications in and out of the cabinet, including start and stop sequences, as well as safety functions. The communication devices, communications, and their set-up are presented in the next chapters in more detail.

3. DATA COMMUNICATIONS OF THE FPC+ CONVERTER

The communications of the FPC+ converter cabinet are reviewed in this section. The communication networks can be roughly divided into local and remote connections. Local connections from outside the cabinet are established with a physical fieldbus transferring information between the cabinet PLC and the WTC (Wind Turbine Controller). Internal connections between the cabinet automation PLC and the primary controls are similarly implemented with fieldbus technology and are in a central role later in the thesis, so they are included in the review. Remote access to the cabinet is offered as an optional feature in the FPC+. It is implemented with special dedicated hardware for creating a secure VPN (Virtual Private Network) tunnel working over the public Internet, enabling the full functionality of the FPC+ cabinet from a remote location without a physical link. The protocols and physical devices to accomplish reliable and secure communications are presented in this chapter, together with some key issues arising due to the nature of the application.

3.1 Local connections

Typically, the converter is controlled via a physical fieldbus using an external wind turbine control PLC, that is not included in the FPC+ converter cabinet. It is the primary control hub which handles the starting and stopping, power or torque references, and monitoring of the converter cabinets connected to the wind turbines. The implementation is typically made by the customer, who might already have a working infrastructure using the same controller, and wants to integrate the new product into the same system. The customer is provided with an interface description to all available signals between them and the FPC+ cabinet automation controller, and are free to access them as seen fit. This section discusses the local, physical connections of the FPC+ converter cabinet, emphasizing the fieldbus technology behind it.

3.1.1 Fieldbus connections

Fieldbus is a term used to describe a standardized set of industrial computer network protocols with a specific hardware interface, designed for real-time distributed control and monitoring of field devices, such as sensors and actuators, and their controllers. In contrast to conventional point-to-point links, fieldbuses offer a multipoint broadcast network which allows bi-directional communication between devices within one communication network. [29] This provides many advantages in comparison with a point-to-point connected network. For example, the network becomes more flexible and extensible, allowing longer distances to be covered and the interoperability of devices from different manufacturers within the same network. Connecting all devices with a single-line network reduces the amount of wiring considerably which leads to substantial cost reductions. Because of the bi-directional nature, fieldbus systems provide means for remote configuration and diagnostics of the devices and information about their condition. [30, p. 91]

FPC+ supports multiple industrial standard protocol choices for the fieldbus connection, such as CANopen, Profibus DP, different varieties of Modbus, EtherCAT, Profinet, and Interbus [27]. Due to the modular nature of the chosen cabinet automation PLC, changing between the fieldbus options is straightforward. The PLC in question is presented in more detail in Section 3.5.1.

Different fieldbuses have different advantages and their own target areas. Typically, the customer already has an established communications network in the field and they want to choose the fieldbus protocol to match that for easier integration to the existing infrastructure. Other deciding factors can be for example the number and distance between nodes, network latency requirements, electrical compatibility issues, usage in hazardous areas, and specific application-level requirements. The fieldbus options for FPC+ are chosen due to their popularity and support in industry.

Data connections inside the converter cabinet, between the primary controls and the cabinet automation control PLC, are implemented using the CANopen fieldbus protocol. In addition, a serial connection is used for control unit parametrization and signal monitoring. Because the CANopen fieldbus protocol is used in the internal communications, it is relevant to the rest of the thesis and will therefore be presented in more detail.

3.1.2 CANopen fieldbus protocol

CANopen is a fieldbus protocol stack based on CAN, comprising high-layer protocols and profile definitions. The CAN protocol is responsible for the two first layers in the Open Systems Interconnection model [35], the physical and the data link layer. The CANopen protocol then takes care of the rest of the layers, the network, the transport, the session, the presentation, and the application layer. [33]

Different layers cover different areas, for example the physical layer has definitions for signal voltage levels, bit encoding, decoding and timings. The data link layer combines bits into frames and handles checksum verification. The concepts of destination addressing and routing are defined in the network layer, and it provides the functionality between the host and the network. The transport layer is responsible for the end-to-end reliability between the host and the destination, and checks for possible failures in communications. The session layer establishes communication sessions for hosts on the networks, and the presentation layer handles data representation and encoding. [34, pp. 18–21]

The application layer is of the highest interest in this thesis, especially the CANopen object dictionary. It is a standardized and structured container that holds configuration and process data, and is required to be implemented in all CANopen devices, as it is the fundamental method which enables CANopen devices to be communicated with. The object dictionary consists of objects that are indexed by a 16-bit index and an optional 8-bit sub-index. The available indices are divided into groups given a 4-digit hexadecimal value according to Table 3.1.

The first non-reserved entries in the object dictionary, indexed with a hexadecimal range of 0001–009F in Table 3.1, are reserved for various data type definitions, such as Boolean, integers of different byte size, floats, strings, date, time, and time difference. CANopen has also specified complex data types for communication and protocol parameters, namely PDOs (Process Data Object) and SDOs (Service Data Object), which are both included in the same data type definitions area of the object dictionary. Additionally, the object dictionary has reserved entries for instance for communication profile in range 1000–1FFF , manufacturer specific profile in range 2000–5FFF, and standardized device profile in range 6000–9FFF. [32, p. 194]

Table 3.1 CANopen object dictionary's 16-bit index breakdown. [32, p. 193]

Hexadecimal Index	Usage
0000	Reserved
0001 – 009F	Data types
00A0 – 0FFF	Reserved
1000 – 1FFF	Communication Profile Area
2000 – 5FFF	Manufacturer Specific Profile Area
6000 – 9FFF	Standardized Device Profile Area
A000 – FFFF	Reserved for further use

The specific structure of the message, the message format, used for every transferred message is defined in the CANopen standard and is based on the CAN frame format. A graphical representation of the format is presented in Figure 3.1.

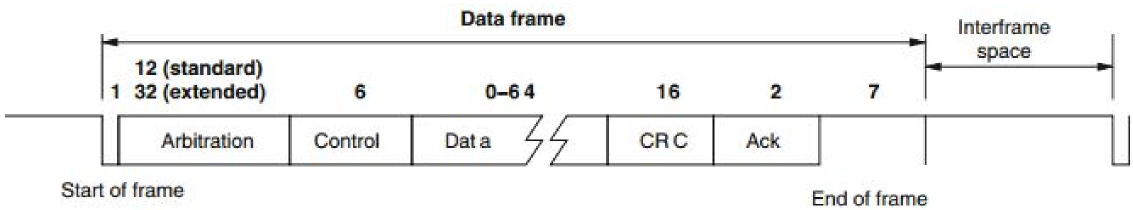

Figure 3.1 The CAN data frame format. [32]

As shown in Figrue 3.1, in standard frames the first 12 bits, after the start of frame bit, is is called the arbitration field. It consists of an 11-bit identifier and a remote transmission request bit. Since version 2.0B of the CAN protocol, an extended frame has been available in addition to the standard frame. CANopen protocol requires that the first 4 bits of the identifier contain the function code of the following 0–64-bit data field. The 7 subsequent bits are the node identification of the transmitting device, which is used to identify the source device. The 7-bit size of the node identification restricts the number of nodes connected to the fieldbus to 127. One CANopen message can contain 0-64 bits of data. Small data size per message allows relatively fast communication speeds up to 1 Mbps, and does not let one message occupy the network for a long period of time. [31]

SDOs are used for directly accessing the object dictionary of the device on the client's initiative. One SDO consists of two CAN frames which are separated by different identifiers, first for the outgoing request, and the second for the confirmation from the accessed device working as the server side in this transmission. [32, p. 198] The SDOs will be used later on in the thesis for developing a parameter exchange functionality between the PLC application and the system software.

PDOs, the process data objects, are used for transferring the time-dependent, high-priority process data, for example sensor readings, commands for controllers, and other control and status information. Similarly to the SDOs, the PDOs are also listed in the object dictionary. In contrast to the SDOs, a PDO consists of only one CAN frame. They are divided into two categories, the TPDOs (Transfer Process Data Object) and the RPDOs (Receive Process Data Object). TPDO is the information created by the node, whereas the RPDO is the data coming to the node from another. PDO transmission can be triggered by different events, for example an internal event of a device, such as an elapsed event timer or exceeding a supervision limit, can trigger the transmission. Transmission can also be triggered upon request, or coupled to a synchronization message. [32, p. 200]

3.2 Remote access

Remote access is an optional feature of the FPC+ cabinet. It enables monitoring and operating of the converter over a TCP/IP (Transmission Control Protocol/Internet Protocol) connection. Everything that is possible to do via local connections, can in principle also be done remotely over the Internet. Practically the only limitation is the provided Internet speed, particularly the uplink speed, that may limit the user experience in some situations. Some precautions should be taken if a wind turbine system is planned to be operated remotely, in case of a lost Internet connection.

The cabinet is fitted with a special remote access device, a Tosibox Lock, that acts as a integrated network switch and router, with a built-in secure VPN utilizing the servers provided by the manufacturer. An Internet connection must be assigned for the Tosibox Lock without forced proxy services or password prompts. [36] The basic idea how the remote connectivity is put into practice in the FPC+ cabinet is illustrated in Figure 3.2.

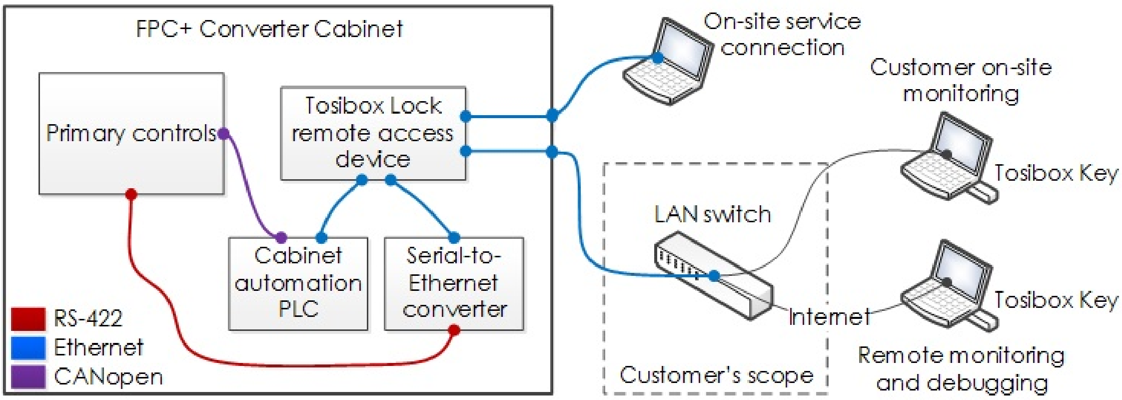

***Figure** 3.2 Illustration of the FPC+ data communications topology. A Tosibox Key is used to restrict access to authorized users only.*

The primary control units communicate with the cabinet automation PLC though a CANopen fieldbus. The fieldbus carries critical signals such as control commands and measurement data between the PLC and the control unit as process data, using the PDO protocol. The primary controls additionally have a standard RS-422 serial communication port, which is used to establish a remote monitoring connection via a serial-to-Ethernet device, Moxa NPort, and the Tosibox Lock remote access device. These devices will be presented in more detail in the following sections. The RS-422 connection carries monitoring signals between the primary controls and for example a control room computer, and is used for parametrization, firmware updates and diagnostic logging when needed. Being able to do all this remotely over the Internet gives the product great flexibility and saves the time and resources of the client.

3.3 Chosen hardware

The principal topology of all the devices used for the internal and external communications of the cabinet was shown in Figure 3.2. The remote access functionality, as well as local monitoring and operation via Ethernet, is based on the Tosibox remote access device. A serial-to-Ethernet conversion needs to be performed to access the primary controls. The devices affiliated with the communications are presented in detail in this section.

3.3.1 Cabinet automation control PLC

Cabinet automation is established using a Beckhoff CX5010 PLC. It is chosen due to its fitting specifications, and the fact that Beckhoff's technology is the most familiar within the company, and know-how for development is readily available. It also has a built-in Ethernet interface for easy integration with the remote access system of the converter cabinet. Beckhoff PLC's have a modular structure that allows installing I/O extension cards to fit any application. The modular nature can be seen in Figure 3.3 featuring a CX5010 with multiple I/O extension cards installed. The extension cards are connected to each other and the main unit via an integrated EtherCAT (Ethernet for Control Automation Technology) bus, which is an Ethernet-based fieldbus system developed by Beckhoff. CX5010's Intel Atom 1.1 GHz processor is seen fit for the task, and practice has shown that it is enough to handle the load without problems. Furthermore, the extended temperature rating of -25–65 °C is suitable in most situations as the air temperature inside the cabinet is never supposed to go over this range. [37]

The CX5010 comes with a TwinCAT 2 runtime and programming environment and although not the newest, it is a very stable and mature environment and fits the purpose. TwinCAT supports all programming languages standardized in the IEC 61131-3, namely LD (Ladder Diagram), FBD (Function Block Diagram), ST (Structured Text), IL (Instruction List), SFC (Sequential Function Chart), and CFC (Continuous Function Chart) [38]. For the most part, ST is used for application development for the FPC+ as it is a high-level, fast and flexible textual programming language allowing complex structures. It is often supplemented with function blocks programmed with FBD, which makes them visually easy to follow and modify. [39]

CX5010 comes pre-installed with Windows Embedded CE 6.0 operating system, which supports enough running processes and virtual memory support needed for FPC+ automation. It has a graphical user interface that is useful during the set-up and when performing diagnostics, and it can be accessed using remote desktop software, or by plugging a monitor and other wanted peripherals to the provided DVI (Digital Video Interface) and USB (Universal Serial Bus) ports. [37]

The 4 installed USB ports can be useful for other purposes than peripheral device connections too. It can be used for example for saving log files on an external hard drive if a logging function is programmed in the application. In the FPC+ such logging feature is planned for the future, including the logging of the grid breaker usage, temperature data, and power histogram. Such information comes handy for example in predictive condition monitoring. This data can then be accessed locally and remotely.

Figure 3.3 *Beckhoff CX5010 PLC with modular I/O extension cards attached.*

3.3.2 Tosibox remote access and networking system

As briefly explained at the beginning of Section 3.2, Tosibox Lock is an integrated network switch and router with a built-in VPN used for setting up secure connections to the cabinet. At the moment, Tosibox offers two models of their product, the Lock 100 and Lock 200. The Lock 200 is an upgraded version of the product and is said to offer better properties for industrial use, including but not limited to a faster VPN throughput, and PoE (Power over Ethernet) functionality. On the other hand, the Lock 200 has inferior operating temperature ratings. While the Lock 100 is rated to operate in temperatures up to 70 °C, the Lock 200 can handle temperatures only up to 50 °C. [36][40] For this reason the older Lock 100 model, presented in Figure 3.4, is chosen for the FPC+. Its properties fit the purpose and the information security is on the same level in both products. Both models of the Lock are fully compatible, so choosing the Lock 100 does not restrict future choices in any way.

One of the main reasons for choosing the Tosibox solution over other choices is that in it everything is integrated into one robust device with secure, audited information security measures. The information security measures taken in the Tosibox solution will be discussed in more detail in Section 3.4. The Tosibox solution also works on a plug-and-go basis and should not require any special expertise to use. It is possible to achieve similar functionality without the Tosibox system by combining different communication devices together, but it would increase costs and add more complexity to the configuration process.

The Tosibox Lock 100 has three RJ-45 -type LAN (Local Area Network) ports for device connections and a WAN (Wide Area Network) port for Internet connection. One port is also provided for service purposes, enabling a direct local connection to the Lock and its settings, which require the administrator password. A wireless LAN access point is built-in with two antenna connections. Additionally, one multipurpose USB port is provided. [36]

The USB port of the Lock can be fitted with 3G (3rd Generation) or 4G (4th Generation) wireless mobile modems for Internet access. It needs to be supplied with a conventional SIM (Subscriber Identity Module) card from an Internet operator of choice. The Lock supports a large variety of different commercial models, and Tosibox also provides its own industry grade models, 3G and 4G, with a variety of mounting options and an external antenna connector. The Lock is designed to automatically recover from a lost connection or modem problems with automatic error detection, recovery and diagnostics functions to minimize downtime and service needs. [41]

Tosibox Lock is paired with the Tosibox Key, an intelligent small USB device with a secure cryptoprocessor, to establish a secure connection between the Lock and the user's PC (Personal Computer). Without the Key, the Lock does not accept remote connections to itself, and only local connections are allowed through the service port or inside the LAN. [36] More details about the serialization process is presented later in the thesis.

During initial commissioning, the Lock needs to be serialized with a Key. This happens automatically by inserting the Key to the USB port on the Lock, and waiting until the notification light on the Key turns off. The procedure should take only around 10 seconds. This first serialized Key becomes the Master Key. If needed, several Sub Keys with wanted privileges can be afterwards serialized using a PC with the Master Key. Multiple Locks can be serialized with one Key. [36]

After the serialized Key is inserted into a PC, its driver and user software is automatically installed. Through the installed user software, the user can connect to any

Figure 3.4 *Tosibox Lock 100 with with a Tosibox Key.*

of the Locks serialized with it and start using all the connected devices remotely in the same fashion as they would be operated locally, fundamentally only limited by the provided Internet connection speed and given access rights. [36, p. 17]

3.3.3 Moxa NPort serial-to-Ethernet converter

Moxa's NPort 5200-series serial-to-Ethernet converter device, illustrated in Figure 3.5, handles the conversion of serial inputs to an Ethernet output. NPort 5232I-T model allows a simultaneous conversion of two RS-422 serial connections to one Ethernet connection. Support for two RS-422 serial ports is needed as in most implementations of the FPC+ the primary controls are composed of two separate units with their own RS-422 serial interface. It is possible to connect to the control units directly through the RS-422 interface, but the NPort converter is included to get all connections behind one Ethernet interface, with the help of the Tosibox Lock. The chosen NPort has an operating temperature range on -40–70 ° C, which is suitable for the task in every situation. The device is small and supports multiple straightforward configuration methods. [43]

Figure 3.5 *Moxa NPort serial-to-Ethernet converter.*

3.4 Information security of the remote access system

Transmission of data over the public Internet always poses threats to the information security of the system. In the case of controlling wind turbines or any similar systems over the Internet, the risk is naturally much more severe and actions must be taken to ensure safety. Tosibox security is audited by an independent global auditing company in accordance with the International Standard on Assurance Engagements 3000, based on the ISO 27001:2013 standard and the Open Software Assurance Maturity Model. [42]

Tosibox Lock and Tosibox Key combination is the core of the remote access in the FPC+ and its information security. During the first physical serialization, the Lock and the Key are cryptographically paired using PKI (Public Key Infrastructure), physically exchanging the public key of the key pair and security certificates, creating a mutual trust relationship. The encryption key is stored securely in the memory of the cryptoprocessor of the Key and is immune to tampering and copying attempts. Subsequent Sub Keys are serialized remotely using PKI and RSA (Rivest-Shamir-Adleman) cryptosystem. After the serialization, Tosibox creates a VPN tunnel between the Lock and the Key, encrypted using the AES (Advanced Encryption Standard) utilizing CBC (Cipher Block Chaining) operation mode. Each data stream between the Lock and the Key is additionally protected with disposable encryption keys using Diffie-Hellman key exchange [26]. When requesting a connection to the Lock using the serialized Key, both devices register to a MatchMaking service administrated by Tosibox. The service then automatically finds the serialized Lock, and establishes the connection if all the prerequisites match. This process is additionally secured by TLS (Transport Layer Security), Diffie-Hellman key exchange and client certificates. This procedure which makes the Lock and the Key identify each other over Internet is a patented method by Tosibox, and is not interfered by firewalls or NATs (Network Address Translation). More details of the used protection techniques are presented in the Table 3.2.

Table 3.2 *Security features and their implementation in the Tosibox system. [42]*

Protection Feature	Implementation
VPN crypto architecture	PKI with 1024/2048/3072 bit RSA keys, physical key exchange
VPN data encryption	AES 128/192/256 bit CBC
VPN control channel encryption	AES 256 bit CBC
Key Exchange	TLS Diffie-Hellman and client certificates
Serializing method (first time)	Physical key exchange
Serializing method (remotely)	PKI, RSA 1024 bit signed
TOSIBOX Lock firewall	Yes (Linux netfilter)
IP/MAC filtering	Yes
Prevent traffic between TOSIBOX Keys	Yes
MatchMaking connection security	TLS with Diffie-Hellman key exchange and client certificates, data encryption AES 256 bit (AES- 256-CBC)
Information privacy	Tosibox Oy does NOT retain any details of customers' devices, private keys or passwords

The protection methods are strong enough to make it practically impossible to establish a remote connection to the Lock without the Key paired up with it. Thus, the only way to access the Lock is through the private, encrypted VPN connection that Tosibox Lock & Key system creates.

The Key is additionally secured with a password prompt to prevent unauthorized access in cases of lost or stolen Key. The password protection is protected against brute force attacks by limiting the number of failed login attempts to six, after which it requests a password change using the PUK (Personal Unlocking Key) code. [36, p. 40]

3.5 Electromagnetic interference of communications

EMC (Electromagnetic Compatibility) is by definition the ability of the system to operate satisfactorily in an environment with electromagnetic fields, without producing detrimental electromagnetic interference to other systems and withstanding electromagnetic emissions from itself and other systems in the same environment. Electromagnetic noise will always exist to some extent and is almost impossible to get completely rid of. The goal of EMC design is therefore to minimize the harmful effects. [44]

EMI can be emitted to the communication cables from external sources or from the operation of the converter itself. EMI can be categorized into continuous and transient or pulse types of interference, and additionally by its coupling mechanism. The four basic mechanisms are conductive, capacitive, inductive, and radiative coupling, and the resulting interference path can be any combination of these mechanisms. [44, p. 5]

Conductive coupling means direct coupling of the signal through a physical mediator such as wiring or common terminals between the emitter and the receiver. Inductive coupling happens when two conductors are magnetically coupled through their mutual inductance by means of electromagnetic induction. Inductive coupling favors transfer of lower frequency components. Higher frequencies are favored by capacitive coupling, which correspondingly means the coupling of two subsystems via a mutual capacitance between them. Conductive surface such as a wire can act effectively as an antenna, and cause unwanted radiative interference propagating through air gaps. [44, p. 6]

Another major form of EMI is the ESD (Electrostatic Discharge), which is a fast burst of energy from the source to the receiver. In the most typical situation, the source is a human who has unknowingly accumulated a big static charge, which then discharges to the target upon touching. The static voltage can build up into tens of thousands of volts, whereas a discharge of only tens of volts can have enough energy to damage or interfere with sensitive circuits. [44, p. 7]

The main concern with EMI in power generation systems is the termination of energy production and financial losses that follow. In some cases, a lost communication link can cause inconvenience or even hazards, if the system suddenly stops receiving commands.

EMC can be improved fundamentally in three ways: removing the source of interference, removing the mediator of interference, or shielding the object susceptible to interference. Most often completely removing the source or coupling path is not possible, so the target is to suppress the emissions and making the coupling path as inefficient as possible. [44, p. 4]

From the viewpoint of the communications, the most important precaution is to select appropriate cables that can survive in active electromagnetic environment. All Ethernet cabling should be shielded in order to cancel out any external EMI. Cable shielding means that all wires inside the cable are enclosed in a common conductive layer of metal foil or braiding, which acts as Faraday's cage, reducing the effects of electromagnetic radiation coming from the outside. The communication cables do not produce such electromagnetic emissions that the cabinet should be protected from them, but the same shielding naturally works in that direction too. [44, p. 546]. The fieldbus cabling as well ought to be shielded against EMI in the same fashion. Typically, all cables are also of twisted pair type, meaning the wires constituting the cable are twisted in pairs in a specific helical structure, which inherently reduces the inductive coupling, and thus crosstalk among the wires. [44, p. 677]

The FPC+ concept has been tested for EMC, including tests for ESD, fast transient voltages, surges, electromagnetic fields, and conducted radio frequencies with methods described in the IEC/EN 61000 standard family [46].

4. CONFIGURATION AND ADMINISTRATION OF THE COMMUNICATION DEVICES

In this chapter, the current configuration methods of the communications are revisited. The conventional way is not suitable in the long term and in mass production, because the method is complex and requires a well orientated engineer to carry it out. Therefore, as one of the main goals of the thesis the configuration method is updated, simplified, and documented so it can be executed by the testing personnel during pretesting without the need for deep knowledge of the system. In preparation for mass production, an administration method for the information gathered during the configuration is implemented.

4.1 Streamlined configuration routine

In preparation for mass production, the configuration routine needs to be simplified and documented. During the prototype phase, all configuration has been done by a trained application engineer using methods that are neither well-documented nor easily explainable to others. The goal is to be able to have the configuration successfully done by anyone given the instructions, without the presence of an application engineer. This makes the pretest and configuration phase more cost-effective and it opens the possibility to easily perform them in any production location with their local personnel.

All steps are documented in detail into an internal document and a simple step-by-step checklist is made to supplement it. Every step in the checklist has a reference to the respective section in the internal document for more detailed information and procedures, for example for personnel performing the configuration for the first time. The checklist also serves as documentation of the configuration procedure, including information regarding the product at hand to be filled by the employee performing the configuration. The checklist is presented in Appendix A.

The configuration routine is one of the first items surfacing from this thesis to bring practical results. It has been successfully carried out in a demanding customer case for multiple FPC+ cabinets. After the initial orientation, the new method was independently executed by the testing personnel without the need for development team help, so it can be deemed successful.

The routine could be further developed to be a more automated process, for example utilizing more batch script files to handle the manual labour of placing the settings. Another idea for further development is studying and testing the DHCP (Dynamic Host Configuration Protocol) functionality of the devices, which could potentially decrease the need for manual IP (Internet Protocol) address configuration if it can be implemented with absolute reliability. However, this could not be done in the scope of this thesis due to lack of time. Further automating the process requires a considerable amount of extra work and the need for it should be studied and decided separately.

The new configuration routine, divided into device specific subsections, is presented below.

4.1.1 Configuration of the Beckhoff cabinet automation PLC

The initial change of the IP address of the PLC used to be done via a remote desktop connection provided by the Windows CE operating system on the PLC. Due to a recent change, the remote connection functionality is rightly disabled by default on all Beckhoff PLCs for information security reasons, and requires additional steps to temporarily enable it. However, the task can be handled in other ways, so it is not necessary to enable it.

The easiest way to perform the initial IP address change is to plug a monitor, mouse, and keyboard directly to the PLC, which is possible with the CX5010 because it provides USB ports and a DVI connection. After that, it is possible to navigate to the network settings of the Windows Embedded CE operating system and manually change the IP address corresponding to the IP address of the Tosibox Lock. The IP addresses need to be in the same IP address space for the communication to work as intended. The Tosibox Lock has a reserved IP address range for this purpose and there are multiple free addresses to choose from right after the Lock's default IP [36, p. 14]. As for the IP of the PLC, the first three octets of the address are the same, and the last octet is increased by two in relation to the Lock's IP. This will be done in the same fashion systematically in all future systems. The subnet mask of the PLC, and of all other LAN devices connected to the Lock, should be set to 255.255.255.192 as per Tosibox's recommendation [36, p. 14].

After the IP address has been set, the latest hardware configuration file and the PLC application software can be downloaded to the device, connecting via the built-in Ethernet port and using the TwinCAT software. A boot project should be created for the PLC of the current application, which means the downloaded application will be automatically started upon every start-up.

4.1.2 Configuration of the Moxa NPort

Moxa NPort serial-to-Ethernet device offers many different approaches for the configuration of the device. Formerly, the device was configured using the ARP (Address Resolution Protocol) command line tool in Windows to map its hardware address with a new IP address. This is a straightforward way for an experienced user, but lacks convenience and fail-safety for trusting the process to be done by anyone. A simple typing error during the ARP mapping via the command line would require more knowledge of the protocol and the command line tool to fix it.

Moxa provides software called NPort Administrator, which makes the configuration more intuitive and easier to adopt. Its most useful feature is the possibility to export the settings of a device, and later import the same settings into another device. This way, after the initial settings are made and tested by the development team, they can be saved to a file and with simple modifications reused in all subsequent devices.

The initial default IP of Moxa NPort is known to be always the same, which simplifies establishing a connection to it. A Windows batch script is made for this purpose, which automatically sets the user's PC to the same IP range with NPort upon activation. After the user's PC is in the same address range, a connection can be made via NPort Administrator, by connecting the PC to the Ethernet port of the device. The provided configuration file, earlier exported from another device, can then be imported into the device currently under configuration. Before applying the new configuration file, the program allows the user to modify the settings. The IP address of the device should be set corresponding to the Tosibox Lock's IP, like is done with the PLC, but in this case increase the last octet by one in relation to the

Lock's IP.

4.1.3 Configuration of the Tosibox Lock

Tosibox Lock has a default IP address, which is left untouched if a client does not request using a specific IP address space. The Lock also has a unique administrator password, which is printed on the Lock itself along with the default IP address. The administrator password is needed for changing the settings of the Lock, but is not itself enough for remote access to the device. Upon assembly of the converter cabinets, the default IP and administrator password are printed on a secondary sticker which will be placed on the top of the Lock for easier access, as the original factory-printed sticker remains inconveniently hidden under the installation rail after assembly.

During pretesting, the default IPs and administrator passwords of all Locks, along with other relevant information gathered during the configuration, are stored in a database file for future usage, with an identifier connecting it to a specific cabinet.

Tosibox provides suitable default settings for the Lock, so the rest of them can be left untouched. It is designed to work as a plug-and-play device so its configuration is very straightforward, and does not need any additional steps. If any problems arise later or a specific customer requires specific settings, further configuration can be done via the web interface of the Lock which has well documented entries.

After all previous steps are done, Tosibox Lock should be instructed to scan all LAN devices connected to it. It can be done by accessing the Tosibox web interface residing in its built-in web server, accessible at its IP address using the administrator password when prompted. After the scan is complete, the connected LAN devices, the Moxa NPort and the PLC, should be renamed accordingly for easier recognition.

4.2 Administration of connections

After the remote connection devices are configured and all the required information about them written down, the data needs to be stored and handled appropriately. The information is made easily accessible and updatable to the personnel who might need it in the future for example in customer support or troubleshooting cases. The required information is listed on the database file itself and only filling in the fields is needed. The needed pieces of information are the Lock's IP address, the Lock's administrator password, internal name of the individual PLC, serial number of the FPC+ cabinet, possible internal production nick name for the cabinet, and names and PUK codes of any new serialized Sub Keys.

The Switch has one dedicated Tosibox Master Key to which all the Locks of the FPC+ cabinets are serialized. The database file of the gathered information is stored on a dedicated test PC. The used test PC is the same in every test, so it is a convenient place to keep the original database, and easily accessible for the testing personnel who has access right to it. The database is periodically synchronized to a backup file on a remote server, which is only accessible to personnel who are considered needing it.

A Backup Key is made from the Master Key and will be stored in a safe place. A Backup Key is a device, which is an exact copy of the Master Key with the same permissions to current Locks and any future Locks the Master Key will be serialized with. The Backup Key will be updated with the Master Key's current serializations and user rights every time it is connected to the Internet. Likewise, the Master Key will be synchronized to the Backup Key in the same fashion if the Backup Key is used to perform new serializations. This behaviour is important to notice to ensure the safe handling of the Backup Key and thus the information security of the system. [36, p. 25] The Backup Key should be needed only in the case of a lost or damaged Master Key.

Sub Keys can be made for the customer, allowing them to connect to the network devices connected to the Locks in their own cabinets. Serialization of a Sub Key is done on a PC with the Master Key, and can be performed at any time and for as many Sub Keys as wanted. During the serialization process, the Key's user interface lets the user to choose which Locks serialized with the Master Key are to be serialized also with the Sub Key. A Sub Key cannot serialize any subsequent Sub Keys. [36, p. 21] Every new Sub Key must be listed to the same database file to help keeping track of them.

The database file created for the purpose is a simple but necessary solution. Initial feedback has revealed that it works for its purpose and is relatively effortless to keep up to date. Its true value will be noticed with time when the amount of entries in it increases considerably. As was noted in the review of the new configuration routine, the administration practices could as well be further automated in the future if necessary. Adding automation to the process would decrease the possibility for human error in the system. However, such development requires extra effort and should be considered only if the current manual process becomes overly laborious with an increasing number of simultaneous cabinets in the production. In that case, it would be a financially justified development step.

In the near future, when the amount of Locks connected to FPC+ cabinets around the world increases, a Tosibox Central Lock could be brought to use. A Central Lock is a special kind of Lock with much higher encrypted throughput capacity in comparison to the normal Lock and a possibility for up to 4000 simultaneous connections, even with overlapping IP addresses. It has a monitoring system for conventional Locks connected into it, and can collect data log from the connected devices for monitoring system usage and generating alarms during possible system disruptions. [45] Using a Central Lock would simplify the administration of a massive amount of Locks. Deeper study of the Central Lock was omitted from the scope of this thesis as currently there is no need for it, but it should be considered in the future.

5. DEVELOPMENT OF THE CABINET AUTOMATION APPLICATION

In this chapter, the FPC+ converter product is enhanced with new features, which will improve the whole system in terms of accessibility and safety. Although the FPC+ is already a complete system, there is some room for improvements and finding and implementing those improvements is one of the main goals of this thesis.

First, a functionality is added that allows the customer to access and modify a set of parameters through the supplied monitoring and parametrization software. This improves the usability of the product greatly, as the customers can themselves modify some important operational parameters that were previously inaccessible without contacting The Switch.

The second development task is a supervision functionality for the cooling fans of the IGBT power modules. The cooling fans are meant to be always running at nominal speed during operation of the converter. A malfunction in any of the fans could lead into early degradation of critical components inside the module, which is why it is important that the operation of the fans is actively monitored.

5.1 Parameter exchange between PLC and primary controls

Remote and local parametrization of the primary controls of the FPC+ is already possible via the supplied software, but some internal parameters of the cabinet automation PLC cannot be changed from their default values without separate software and the source code of the application. This is not a convenient situation from the clients' perspective if they want to change the default values, so as a part of this thesis the data communication between the primary controls and the automation PLC is improved to support parameter exchange between the devices exploiting the SDO protocol of CANopen.

As the primary controls of the converter and the automation PLC use the CANopen fieldbus for data communications, they support the SDO communication as explained in Section 3.1.2. The interface for the SDO communications of the FPC+ primary controls is well documented in an internal document [47] and the CANopen object dictionary object is already created, but the implementation is missing from the automation PLC application. The interface follows the CANopen standard, and as the PLC's Intel Atom processor is based on Intel x86 processor architecture, they both use little-endian bit representation [34, p. 93][48, p. 7]. Little-endian representation means that the least significant byte of a word is stored first in the lowest memory address and the following bytes are stored into the memory in order of increasing significance. Knowing the byte order of both ends of the communication link is essential for programming purposes, but does not concern the customer. The byte order being the same in both ends simplifies the programming work, as bit rotation functions are not required.

Beckhoff's ADS (Automation Device Specification) interface can be used directly to transfer SDO messages between connected devices. Two library functions are readily available in TwinCAT 2 programming environment to perform read and write operations, which makes the software implementation easier. They are called ADSREAD and ADSWRITE, and their function block diagrams are presented in Figure 5.1. [51]

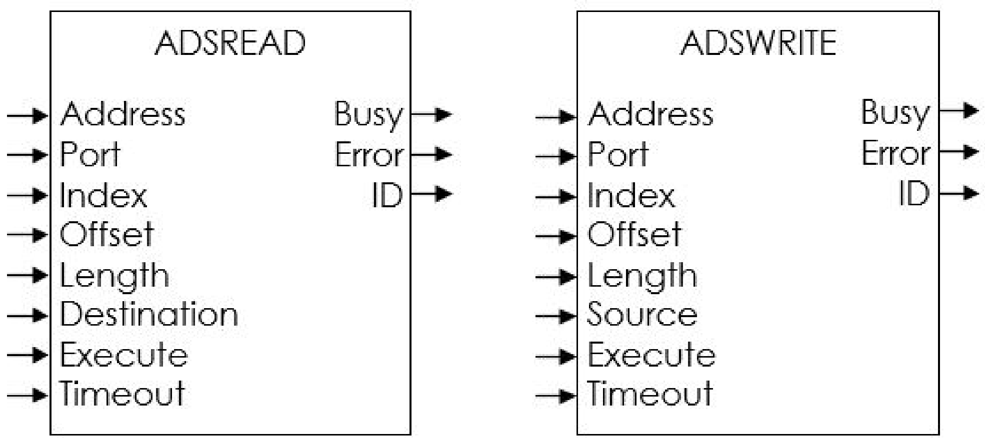

Figure 5.1 *TwinCAT PLC Control's own ADSREAD and ADSWRITE function blocks for inter-device message exchange. Function block inputs on the left side of each block, and outputs on the right side. [51]*

As can be noted, both functions are very similar. They take address information of the destination device, CANopen object dictionary indices, function triggers and other supplementary information as inputs, and give information about the status of the current message as an output. Reading one user defined parameter from the primary controls requires three ADSWRITE function calls and one ADSREAD function call. The first two write function calls set the desired parameter group identification and parameter identification, respectively. The third write function call then executes the reading command. Finally, with the last read function call, the value of the parameter is read to the reserved variable set in the Destination input of the function block. Writing a parameter to the controls is possible in similar fashion with four ADSWRITE function calls, but such functionality is not needed in this case. [47] However, if planned for the future, the basic implementation is ready and can be used for this purpose with minor modifications.

The PLC automatically reads the user parameters from the primary controls during every power-up, and stores them in an array, from which they are then individually accessed and assigned to their respective PLC parameter. After the whole user parameter list has been downloaded without errors, a variable indicating a successful download is set true, and the program is no longer executed. The control software has a functionality that detects when the user changes a parameter, and sets a bit in the main status word to 1. The bit retains this value until no more changing parameters are detected during a set time period, and returns to 0 afterwards. The PLC application is programmed to detect this falling edge of the bit, and to start reading the parameter list again to update the changed user parameters.

Suitable timing had to be tested for the read cycle. The function block cannot read the user parameters with the speed of the PLC task cycle time, which is 1 ms. Reading the parameter successfully takes more time. Too fast cycle results in some parameters to be skipped and sometimes wrong values to be read to wrong parameter indices. A pacemaker functionality is added to call the function block periodically, and the timing is adjusted until no errors occurred during long test periods of subsequent reads. For testing purposes all parameter values are set matching their indices, and an automatic testing function is added to repeatedly read the parameter array and to check that every parameter index and its value matches, and formatting the array to zeros in between every read. Around 50 ms read cycle proved to be reliable, resulting in zero wrong values in over ten thousand subsequent read cycles. Zero tolerance for read errors is set as a design premise as reading a wrong parameter value to wrong parameter index could potentially cause errors in converter operation. Typically, the parameters are changed only rarely, as they are already set to optimal values before shipping. This means that the user parameter values need to be read rarely, so zero read errors in ten thousand reads can be considered a reliable test result.

Finally, each parameter is assigned a unique identification number and name in the user parameter section. Each parameter is given a sane default value, but customer is free to change them in the given limits. A tooltip is added to each parameter to provide more information in addition to the limited parameter name.

The parameter exchange functionality was successfully implemented and owes much to the good documentation of the interface between the primary controls and the PLC and the base work done by others. It has been tested to work as designed and without burdening the processor of the PLC noticeably. The feature can be further developed to fetch other informational data from the primary controls if wanted, but it is not necessary in the scope of this thesis. Also exchanging parameters in the other direction, from the primary controls to the PLC, can be further investigated if it has some possible benefits that could be implemented later.

5.2 Power module cooling fan condition monitoring

During operation, the power modules produce a lot of heat. The switching of the modulating IGBTs is not an ideal event, and thus part of the energy is wasted as thermal energy. Moreover, the conductors have a nonzero resistance which leads to ohmic losses when current is flowing through, further heating up the metal body of the power module. This accumulated heat must be dissipated effectively with forced cooling to prevent overheating of the IGBTs, that typically have a maximum junction temperature of around 175 °C. In addition to possible damages and accelerated aging caused by overheating, the conduction and switching losses in semiconductors increase proportional to temperature, so it is generally desired to keep them operating as cool as possible to achieve optimal efficiency. [50] In order to effectively monitor the operation of the fans, a condition monitoring functionality is added to the cabinet's automation application. The information about any problems is then sent to customer's wind turbine control via the fieldbus.

The FPC+ cabinet is a closed airtight system, and the IGBTs are liquid cooled. The

IGBTs are connected to a heat sink which transfers the heat energy to the ethylene glycol and water cooling medium mixture. The cooling liquid then transfers the heat outside of the cabinet, where it is dissipated by the liquid cooling system. The power modules also have built-in cooling fans to forcedly convect the amassed heat to avoid hot spot formation inside the modules, and to cool down the DC-link capacitors. They work in synergy with the cabinet's own air blowers to move the air inside the cabinet, allowing excess heat to transfer outside via the water cooling system. Without the fans, hot spots would start to form, overheating the modules, and possibly causing system fault protections to trigger that lead to power production downtime. Standstill fans have also been measured to increase the DC-link capacitor temperatures over their designed limit, which decreases their lifetime. To add extra protection to the system, a cooling fan rotation supervision is implemented.

The power module cooling fans have few different starting triggers. They are always blowing when grid side breaker is closed, or if any measured temperature inside the cabinet exceeds its optional temperature limit programmed to trigger the fans. They are also forced to rotate when humidity conditions inside the cabinet require it.

The used DC fans are standard 4-wire fans, meaning their speed can be controlled via the PWM input pin and their actual rotation speed can be monitored via the tachometer output pin. The output signal behaviour of the tachometer pin is explained in the user manual of the cooling fans [49, p. 168], and an illustration of it is presented in Figure 5.2.

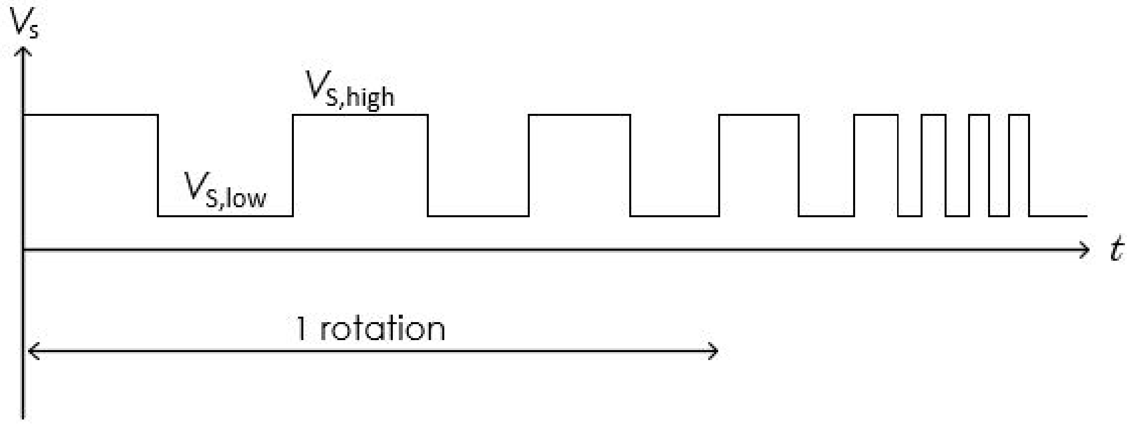

Figure 5.2 *Diagram of the tachometer output signal waveform. Voltage V_s on the y-axis changes between the low and high levels with respect to time t with frequency that is proportional to the fan speed.*

As from Figure 5.2 can be noted, the tachometer signal generated by the fan is a square wave with specific voltage levels describing the low and high status on the signal, $V_{s,low}$ and $V_{s,high}$, respectively. One full revolution of the fan generates 3 periods of said signal. The faster the fan rotates, the higher is the frequency of the generated square wave. The internal functionality of the fan was simulated in LTspice software to help to understand the mechanism and to choose right components for the implementation. The simulation model is presented in Figure 5.3.

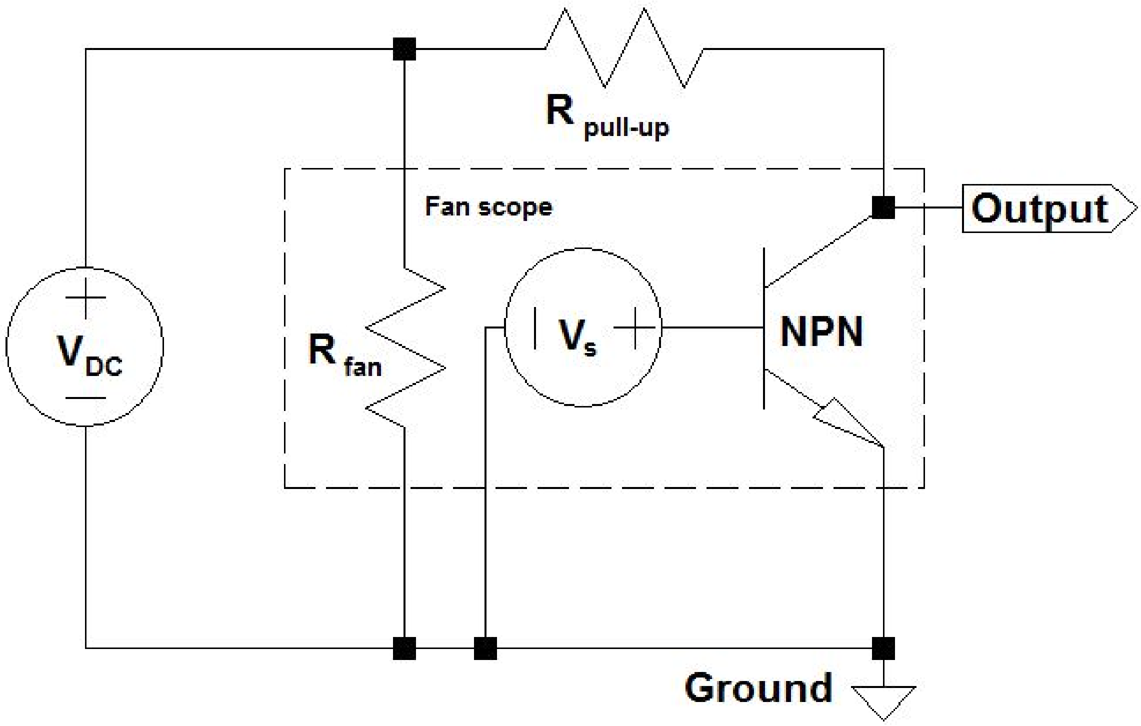

Figure 5.3 *A rough LTspice model for simulating the open collector output of the DC fan tachometer. Dashed line rectangle represents the scope of the supplied fan.*

For the accuracy needed in preliminary testing of the implementation, it is enough to model the fan itself as a plain resistor with resistance R_{fan}. In addition, the tachometer is modelled as a voltage pulse generator with voltage V_s and a NPN type transistor. Together the fan and the tachometer model composes the fan scope, marked with a dashed line in Figure 5.3. The simulation model enlightens the way the tachometer pulse is generated. The NPN type voltage controlled transistor is connected from its base to the fan's internal circuitry. The fan rotor has embedded magnets, in this case three of them, that upon bypassing a Hall-effect sensor generate a voltage pulse in it, which is then amplified and sent to the base of the transistor. The transistor is rated for this voltage level, and every time it receives a voltage pulse, it starts sinking current from its collector to its emitter. The collector is externalized from the system, and the user has direct access to it. This is called an open collector output, typically found on integrated circuits.

The open collector output signal as it is may not be of adequate level for the system interpreting the signal, as is the case in here. Thus, the output must be connected to the 24 V DC line, V_{DC}, via a pull-up resistor $R_{\text{pull-up}}$ as shown in Figure 5.3. This way, when the transistor is not conducting, the open collector output will be pulled up to 24 V, which is the low voltage level used by the control electronics in the FPC+ cabinet. When the transistor conducts, it will sink the voltage potential to ground, and the open collector will output a voltage level close to zero. The signal frequency can be calculated from equation

$$f = \frac{3n}{60}, \tag{5.1}$$

where n is the rotation speed, in this case 9500 RPM (Revolutions Per Minute), which is the nominal speed of the fan at rated voltage. The multiplication by 3 comes from the aforementioned fact that the open collector outputs three signal periods per rotation. When substituting the nominal rotation speed $n = 9500$ RPM to the Equation 5.1, the signal frequency f equals 475 Hz, translating to period of 2.1 ms when inversed. This information is important for planning the hardware and software implementations for the RPM calculation.

5.2.1 Hardware implementation for fan supervision

The tachometer signal frequency calculated from Equation 5.1 is needed to choose the right digital input terminal card for the PLC. The digital input terminals used with Beckhoff PLCs have typically been the EL1008 model, providing 3 ms input filtering time and eight input terminals. The 3 ms input filter time is optimal for mechanical switches because it filters out unintentional noise, but for counting fast signals it is inadequate. As calculated before, in this case the signal period time is 2.1 ms, which sets the low limit for the input filter time. Practical tests with the EL1008 card with 3 ms input filter time showed that it indeed is too slow for this purpose, as it could not see the varying pulse from the fan tachometer. It registered only a steady signal, from which neither the fan speed nor its state could be determined.

Beckhoff's EL1018 digital input terminal provides 10 μs input filtering time, which means it can read the input oscillating at 100 kHz frequency, definitely enough for this case as the task cycle of the PLC software by itself limits the scan time to 1 ms. A test piece was ordered to verify its functionality, and it proved to work as expected. In contrast to EL1008, the EL1018 registers every pulse and thus allows the software implementation to calculate the fan's rotation speed with good accuracy. It has eight inputs, so with one extension terminal all four cooling fans of the four power modules can be monitored. More about the software implementation will be discussed in Section 5.2.2.

The second hardware design question is about deciding the optimal value for the pull-up resistor used in the circuit shown in Figure 5.3 and briefly explained in Section 5.2. The value of the pull-up resistor affects several things. The sink current of the transistor is inversely proportional to this resistance as per Ohm's law

$$I = \frac{V}{R}, \tag{5.2}$$

where I is current, V is voltage and R is resistance. According to the manufacturer's datasheet, the maximum sink current I_s the transistor can handle is 20 mA. As the operating voltage V_n is known to be 24 V and the residual voltage V_r when the transistor is conducting is known to be maximum 0.4 V, the minimum value for the pull-up resistor $R_\text{pull-up}$ can be calculated from

$$R_\text{pull-up} = \frac{V_\mathrm{n} - V_\mathrm{r}}{I_\mathrm{s}}. \tag{5.3}$$

It is not however beneficial to choose the lowest possible resistor value and keep the sink current at its maximum [53, p. 180], and should only be considered if the switching speed of the system is critical. Raising the pull-up resistor value too high increases the transient response time of the circuit, as it acts like the resistance in a resistance-capacitance oscillator circuit. This means as the resistance increases, the time it takes for the voltage to change between logical 0 and logical 1 levels also increases. [52, p. 678]

The voltage levels for logical 0 and logical 1 are found in the documentation of the digital input terminal. Logical 0 is registered with input voltages between -3 V and

5 V. Logical 1 is registered between 15 V and 30 V. The digital input terminal is a current sinking type, and in addition to a sufficient voltage level it requires a minimum current to reach the logical 1 level. According to the documentation, this level is typically around 3 mA, so this is used in calculations as the minimum current. In conclusion, the pull-up resistor must be large enough to ensure that the sink current specification of the transistor is not exceeded, but small enough not to decrease the voltage and current level in the digital input terminal, and to allow fast enough voltage change time to fit the application [52, p. 678].

Arbitrarily choosing a safe value of 10 mA for the I_s, between the minimum 3 mA and maximum 20 mA previously explained, Equation 5.3 gives with the known voltage values $R_\text{pull-up} = 2\,360\ \Omega$. The closest standard resistor value readily available in supply is $2\,200\ \Omega$, so it is chosen for further inspection. In tests, it was found to be a working choice.

The power rating for the $R_\text{pull-up}$ can be chosen based on equation

$$P = \frac{V_\mathrm{n}^2}{R_\text{pull-up}}, \tag{5.4}$$

where P is the active power that is dissipated in the chosen resistor when voltage V_n is applied over it. Substituting the known values $R_\text{pull-up} = 2\,200\ \Omega$ and $V_\mathrm{n} = 24$ V to Equation 5.4, the dissipated power is shown to be $P \approx 0.262$ W. This is the minimum value for the power rating of the resistor. A standard $\frac{1}{4}$ W resistor type is thus too weak, but a standard $\frac{1}{2}$ W resistor suffices.

5.2.2 Software implementation for fan supervision

The software implementation for the PLC is finalized after the needed hardware is chosen and the operation idea is outlined. The function block handling the fan supervision is written in ST language and added to the PLC application project. A simplified algorithm describing the functionality is shown in Appendix B. Basically, a signal counter function calculates every rising edge of the signal waveform that is inputted to the EL1018 card. Then, the amount of rising edges in each time frame of one second is calculated. In the specification of the fan it is told that the tachometer outputs three rising edges per revolution, so it is possible to calculate the revolutions per second with this information by dividing the amount of rising edges in the one second time frame by three. To get the final RPM value, the result is multiplied by 60 seconds. With the final RPM value available, it is straightforward to add any wanted limits for alarm or fault creation.

A signal indicating a fan stoppage or excessive slowdown is sent through the internal fieldbus to the primary controls, where it is designated a fault code and name. A 16-bit value is also sent through the external fieldbus for the customer's WTC for easier identification of the faulty fan. The information is sent as an integer value, from which can be interpreted the malfunctioning fan. When this integer is viewed as a binary value, each bit represents one fan, starting from the least significant bit. When the respective bit is 0, the fan is functioning normally. When the bit is 1, the fan is malfunctioning. When all fans are working normally, the integer is 0 in decimal form.

Most of the work can be done inside loop structures, which makes the code easily expandable for future, for example if the number of monitored fans changes. This is highly likely in situations where multiple cabinets are used in parallel, but only one cabinet has a PLC and the rest of the cabinets are connected to the master PLC via remote I/O terminals.

A spare 4-wire cooling fan is set up as a preliminary test arrangement for testing the software functionality and debugging it, as it is much more accessible compared to the high speed and loud cooling fans used in the cabinet itself, yet very similar in functionality.

After the hardware configuration is finalized and the application debugged, the functionality is tested with an actual FPC+ cooling fan spare part to ensure the functionality and test for any unexpected software bugs. As everything works as designed, the solution is included into the product. It was tested during functional tests of a FPC+ cabinet and verified to work as planned with four cooling fans connected at the same time. The RPM values are accurate enough for supervision purposes, and the fault creation logic works as planned.

Controlling the speed of the fan is not implemented in the scope of this thesis as the manufacturer of the power modules recommends using the fans at nominal speed at all times and has documented the technical performance based on that assumption. However, it is typical in wind power use that the converter is not operating at full power constantly because of fluctuations in wind conditions, so it might be beneficial for the lifetime of the cooling fans to rotate them slower at partial loads. The speed control requires additional hardware for controlling the PWM input of the fan and additional software development. However, if planned in future, it can be used well in synergy with the implemented rotation speed calculation functionality.

6. CONCLUSIONS

An overview of the theory and practices of the predominant technologies used in many products of The Switch is presented in the second and third chapters. In addition to giving the reader prerequisite information for better understanding the rest of the thesis, the theory chapters work as an introduction to the system for new and old employees who are interested in learning the basics. The theory presented in these chapters does not go very deeply into the subject, what might obscure the overall picture of the topic. However, further expanding the theory does not serve any purpose for the rest of the work, so it is suggested that the related citations of each topic are followed for more information.

The basic theory being outlined, the thesis continues with developing the way the communication devices are set up and administrated, which requires some thought and work to achieve the best results and maintaining information security and accessibility in the long-term. The fourth chapter introduces new configuration and administration methods making this work phase more efficient and straightforward, and keeping the collected information in order. This was one of the main objectives of the thesis. With the renewed routines and documentation, the testing personnel can perform all the steps without the need for a development team intervention at any point. This helps to keep the usable resources concentrated on the work where they are the most needed. With the documentation and checklists, the procedure could be transferred to any of the company's overseas facilities or to a subcontractor with relative simplicity if wanted. The developed routine has already been put to test in practice with a demanding customer case and it was proven to be effective. After the initial training, several FPC+ cabinets were independently configured by the testing personnel. Confirming the real effect of the administration system requires more time to accumulate a big amount of entries into the database, but according to the initial feedback, it has been effortless to use.

To further develop the FPC+ product to meet the needs of customers, two product development tasks were carried out within the scope of this thesis as another main objective. The fifth chapter presents the implementation of a parameter exchange functionality between the cabinet automation logic and primary controls, and a supervision functionality for the power module cooling fans.

The parameter exchange exploits the reserved service data objects of the CANopen protocol and the automation device specification protocol deployed by Beckhoff Automation. It allows the customer to modify the parameters related to the cabinet automation logic, using the monitoring and parametrization software shipped with the product. This was formerly impossible without access to the source code of the PLC application itself, thus being only accessible to the application development team of The Switch. Opening some of the essential parameters to the customer makes the FPC+ product more flexible and saves time from both parties, the supplier and the customer. The functionality has been tested in internal tests and verified to work reliably. The implementation could be further expanded to carry more information from the primary controls to the PLC if considered useful. This information could then be delivered to the customer's wind power controller via the fieldbus connection. All the needed functionality to achieve this was developed in the scope of this thesis, and accessing this information only requires some variable changes in the application. Exchanging information in the other direction, from the PLC to the primary controls, was implemented at the same time, but all actual higher level usage was omitted due to lack of time. However, it is a good basis on the future development of the FPC+ product.

The second product development task is related to the condition monitoring of the power module cooling fans designed to prevent hot-spot formation within the modules, and to keep the DC-link capacitors at optimal temperature. Exceeding the optimal temperature decreases the lifetime of the capacitors and leads to premature component failure and superfluous maintenance costs. To prevent this, a supervision functionality for the fans was added to the product. The fans have a standard 4-wire assembly, meaning they have a tachometer output as well as a PWM input for speed control. Interpreting the tachometer output signal, however, is not included in the scope of the fan manufacturer. The manufacturer provides the interface description and electrical drawings, on which the implementation was carried out. The result of the task was successful, and the functionality works as planned. The chosen new hardware is working as wanted while being a cost-effective choice. The application gives accurate measurements of the rotation speeds of each fan, and the fault indication works according to design.

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APPENDIX A. FPC+ COMMUNICATION DEVICE CONFIGURATION CHECKLIST

FPC+ remote access device configuration checklist

for new cabinets

Product:		**Test date:**	
S/N:		**Place:**	
Tester:		**Approved:**	

Write down the IP addresses of the remote access devices

Device	IP-address	Instructions
Tosibox Lock:	0.0.0.0	Default IP on the label if not otherwise instructed
Moxa Nport:	0.0.0.1	+ 1 to the last octet of Lock's IP
Beckhoff PLC:	0.0.0.2	+ 2 to the last octet of Lock's IP

Please refer to the attached documentation in each step!

#	Reference	Instructions	OK
1	2.3.2.	Plug in a monitor, keyboard and mouse to the Beckhoff PLC and change it's IP address	
2	2.2.1.	Plug in an Ethernet cable directly to Moxa Nport, and Run the script file named "Moxa IP" to change your PC's IP, or do it manually	
3	2.2.1.	Start NPort Administrator software and find the Moxa connected. Import the "Moxa Config" file and do the necessary modifications	
4	2.3.3.	Change the Ethernet cable from Moxa to the external socket on the side of the cabinet, and run the script file named "DHCP" to change your PC's IP, or do it manually	
5	2.3.3.	Start TwinCAT System Manager and activate the hardware configuration	
6	2.3.4.	Start TwinCAT PLC Control and upload the PLC project	
7	2.3.5.	Write down the Tosibox Lock's default IP and password in the database file	
8	2.3.5.	Open Tosibox web configuration, log in, and scan for LAN devices	
9	2.3.5.	Rename the LAN devices to "Moxa Nport" and "Beckhoff PLC" accordingly	

Comments:

Figure A.1 *Step-by-step checklist for the testing personnel for straightforward routine.*

APPENDIX B. ALGORITHM DESCRIBING THE FAN SUPERVISION FUNCTION

```
// Define and initialize signal counters
SignalCounter(IN := FanDigitalSignal, OUT := FanCounterValue);
// Count pulses during 1 second time frame
IF OneSecondElapsed THEN
  PulsesInSecond := FanCounterValue - FanCounterValuePrevious;
  FanCounterValuePrevious := FanCounterValue;
END_IF;
// Determine RPM value from calculated signal density
FanRPM := 60 * (PulsesInSecond / 3);
// If RPM decreases below a set limit, send signal to
// another function block deciding when to create a fault
IF FanRPM < FanRPM_LowLimit THEN
  FanMalfunctionSignal := TRUE;
ELSE
  FanMalfunctionSignal := FALSE;
END_IF;
// Similarly for all existing fans
```

Algorithm B.1 *Simplified algorithm for fan rotation speed supervision and warning signal generation for a single fan.*