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Multilevel Power Converters with Smart Control for Wave Energy Conversion

DEEPAK ELAMALAYIL SOMAN

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2017

ISSN 1651-6214
ISBN 978-91-513-0146-4
urn:nbn:se:uu:diva-332730

Dissertation presented at Uppsala University to be publicly examined in Room 80101, Ångströmlaboratoriet, Lägerhyddsvägen 1, Uppsala, Monday, 4 December 2017 at 13:15 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract

Elamalayil Soman, D. 2017. Multilevel Power Converters with Smart Control for Wave Energy Conversion. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1597. 98 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-0146-4.

The main focus of this thesis is on the power electronic converter system challenges associated with the grid integration of variable-renewable-energy (VRE) sources like wave, marine current, tidal, wind, solar etc. Wave energy conversion with grid integration is used as the key reference, considering its high energy potential to support the future clean energy requirements and due the availability of a test facility at Uppsala University. The emphasis is on the DC-link power conditioning and grid coupling of direct driven wave energy converters (DDWECs). The DDWEC reflects the random nature of its input energy to its output voltage wave shape. Thereby, it demands for intelligent power conversion techniques to facilitate the grid connection.

One option is to improve and adapt an already existing, simple and reliable multilevel power converter technology, using smart control strategies. The proposed WECs to grid interconnection system consists of uncontrolled three-phase rectifiers, three-level boost converter(TLBC) or three-level buck-boost converter (TLBBC) and a three-level neutral point clamped (TLNPC) inverter. A new method for pulse delay control for the active balancing of DC-link capacitor voltages by using TLBC/TLBBC is presented. Duty-ratio and pulse delay control methods are combined for obtaining better voltage regulation at the DC-link and for achieving higher controllability range. The classic voltage balancing problem of the NPC inverter input, is solved efficiently using the above technique. A synchronous current compensator is used for the NPC inverter based grid coupling. Various results from both simulation and hardware testing show that the required power conditioning and power flow control can be obtained from the proposed multilevel multistage converter system.

The entire control strategies are implemented in Xilinx Virtex 5 FPGA, inside National Instruments' CompactRIO system using LabVIEW. A contour based dead-time harmonic analysis method for TLNPC and the possibilities of having various interconnection strategies of WEC-rectifier units to complement the power converter efforts for stabilizing the DC-link, are also presented. An advanced future AC2AC direct power converter system based on Modular multilevel converter (MMC) structure developed at Siemens AG is presented briefly to demonstrate the future trends in this area.

Keywords: Multilevel power converter, FPGA control, Wave Energy, Three-level boost converter, Three-level buck-boost converter, Variable-renewable-energy, Three-level neutral point clamped inverter, Linear generator, DC-link, AC2AC direct converter, Modular multilevel converter

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ISSN 1651-6214
ISBN 978-91-513-0146-4
urn:nbn:se:uu:diva-332730 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-332730)

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I L. A. Vitoi; R. Krishna; **D. E. Soman**; M. Leijon; K. Kottayil, "Control and implementation of three level boost converter for load voltage regulation," *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna,* pp. 561-565, 2013.

II R. Krishna; **D. E. Soman**; S. K. Kottayil; M. Leijon, "Pulse delay control for capacitor voltage balancing in a three-level boost neutral point clamped inverter," *IET Power Electronics*, vol.8, no.2, pp. 268-277, 2015.

[*The IET Power Electronics Premium Award 2016*]

III **D. E. Soman**; R. Krishna; M. Leijon; K. Vikram; S. K. Kottayil; L. A. Vitoi; J. G. Oliveira; S. S. Kumar, "Discontinuous conduction mode of a three-level boost DC-DC converter and its merits and limits for voltage cross regulation applications," *IECON-40th Annual Conference of the IEEE Industrial Electronics Society*, *Dallas, TX*, pp. 4268-4272, 2014.

IV **D. E. Soman**; M. Leijon, "Cross-Regulation Assessment of DIDO Buck-Boost Converter for Renewable Energy Application," *Energies*, vol. 10, no. 7, p. 846, 2017.

V **D. E. Soman**; K. Vikram; R. Krishna; M. Gabrysch; S. K. Kottayil; M. Leijon, "Analysis of three-level buck-boost converter operation for improved renewable energy conversion and smart grid integration," *IEEE International Energy Conference (ENERGYCON)*, *Cavtat,* pp. 76-81, 13-16 May 2014.

VI I. Dolguntseva; R. Krishna; **D. E. Soman**; M. Leijon, "Contour-Based Dead-Time Harmonic Analysis in a Three-Level Neutral-Point-Clamped Inverter," *IEEE Transactions on Industrial Electronics*, vol.62, no.1, pp. 203-210, 2015.

VII R. Krishna; **D. E. Soman**; S. K. Kottayil; M. Leijon, "Synchronous Current Compensator for a Self-Balanced Three-Level Neutral Point Clamped Inverter," *Advances in Power Electronics*, vol. 2014, Article ID 620607, 8 pages, 2014.

VIII **D. E. Soman**; J. Loncarski; M. Srndovic; M. Leijon, "DC-link stress analysis for the grid connection of point absorber type wave energy converters," *International Conference on Clean Electrical Power (ICCEP)*, *Taormina*, pp. 61-66, 16-18, June 2015.

IX J. Loncarski; **D. E. Soman**, "Interconnection Strategies of Point Absorber Type Wave Energy Converters and Rectifier Units." [*Submitted to 18th International Conference on Harmonics and Quality of Power.(ICHQP2018)*].

X Y. Hong; E. Hultman; V. Castellucci; B. Ekergård; L. Sjökvist; **D. E. Soman;** R. Krishna; K. Haikonen; A. Baudoin; L. Lindblad; E. Lejerskog; D. Käller; M. Rahm; E. Strömstedt; C. Boström; R. Waters; M. Leijon. "Status Update of the Wave Energy Research at Uppsala University," *10th European Wave and Tidal Conference (EWTEC)*, Aalborg, Denmark, September, 2013.

XI **D. E. Soman**; J. Loncarski; L. Gerdin; P. Eklund; S. Eriksson; M. Leijon, "Development of Power Electronics Based Test Platform for Characterization and Testing of Magnetocaloric Materials," *Advances in Electrical Engineering*, vol. 2015, Article ID 670624, 7 pages, 2015.

XII **D. E. Soman**; M. Leijon, "Kalman Filter Based Grid Synchronization in Stationary Reference Frame" [*To be submitted*].

Contents

Abbreviations

AC	Alternating current
AC2AC	AC to AC
ADC	Analog to digital converter
APOD	Alternative phase opposition disposition
ARS	Asymmetrical regular sampling
CBPWM	Carrier based pulse width modulation
CCM	Continuous current mode
CPWM	Carrier pulse width modulation
DAC	Digital to analogue converter
DC	Direct current
DCM	Discontinuous current mode
DDLPMG	Direct drive linear permanent magnet generator
DDWEC	Direct drive wave energy converter
DIDO	Dual input dual output
EMC	Electromagnetic compatibility
FPGA	Field programmable gate array
GUI	Graphical user interface
HVDC	High voltage direct current
I/O	Input output
IGBT	Insulated-gate bipolar transistor
LPMG	Linear permanent magnet generator
MIMO	Multi input multi output
MMC or M2C	Modular multilevel converter
MOSFET	Metal–oxide–semiconductor field-effect transistor
NPC	Neutral point clamped
NS	Natural sampling
PCC	Point of common coupling
PD	Phase disposition
PDC	Pulse delay control
PI	Proportional integral
PLL	Phase locked loop

POD	Phase opposition disposition
SCC	Synchronous current control
SIDO	Single input dual output
SRS	Symmetrical regular sampling
SSPDC	Switch signal phase delay control
SVM	Space vector modulation
THD	Total harmonic distortion
TLBBC	Three-level buck-boost converter
TLBC	Three-level boost converter
TLBNPC	Three-level boost neutral point clamped
TLNPC	Three-level neutral point clamped
VHDL	VHSIC (Very high speed integrated circuit) hardware description language
VRE	Variable-renewable-energy
VSC	Voltage source converter
WEC	Wave energy converter
WTHD	Weighted total harmonic distortion

Nomenclature

Symbol	*Units*	*Description*
C	F	Capacitance
C_s	F	Snubber capacitance
d	-	Duty ratio
e_v	V	Voltage error
F_s	Hz	Sampling frequency
F_{sw}	Hz	Switching frequency
I_d	A	Diode current
i_L	A	Load current
K_i	-	Gain constant for integral controller
K_p	-	Gain constant for proportional controller
L	H	Inductance
R	Ω	resistance
R_s	Ω	Snubber resistance
T_d	s	Dead-time
T_s	s	Sampling time
V_d	V	Diode voltage
V_{dc}	V	DC Voltage
V_{dref}	V	Direct axis reference voltage
v_{in}	V	Input voltage
v_L	V	Voltage across inductor
V_{np}	V	Voltage at the neutral point of NPC
V_o	V	Output voltage
V_{ref}	V	Reference voltage
ΔV	V	Unbalance voltage
λ	-	Pulse delay ratio

1 Introduction

1.1 World energy scenario

The global energy sector has been undergoing a paradigm shift in recent years. Disruptive trends are emerging in the energy industry, mainly driven by the vision of sustainable development. Greater environmental and climatic challenges as well as radical new technologies are pushing towards clean energy technologies by replacing conventional ones for the sustainable future. Historical trends and future projections of the total world energy consumption by different energy sources are published in various energy outlook reports. International Energy Outlook 2016 by U.S. Energy Information Administration [1], World Energy Outlook 2016 by International Energy Agency [2] and BP Energy Outlook from BP [3] are some of the notable examples in this area. All of them are suggesting the growth rate of renewables in general, will be ramping up in the future.

1.2 Electric power generation and renewables

More than half of the increase in global energy consumption is used for power generation as the long-run trend towards global electrification continues. In the energy market, all fuels compete for the evolution of a cost effective global fuel mix. Power generation is one of the main sectors for competition. The share of renewables used for power generation is increasing significantly. Wind, solar and hydropower are the most established renewable energy sources used for the power production presently. Wave, tidal, marine current and hybrid types are the most anticipated sources for the future.

1.3 Wave energy

Energy extraction from sea waves has gained a lot of attention in recent years. It has become one of the fastest growing research areas. This is also one of the most challenging energy sources to interface with the grid due to the complexity in the energy extraction mechanism and the highly random nature of input energy. The essential requirement to capture this energy is the right technology at the right place. Mainly two branches of studies are ongoing in ocean energy research. The first is in the energy resources assessment and market studies [4], while the second topic focuses on new technology development and testing.

Many wave energy converter (WEC) technologies have now been developed and tested around the world [5]; see Figure 1.1. The technologies vary in operating methodology as well as in physical dimensions. Classifications of such technologies are made based on various factors. Distance of the WECs from the shore can be one of the criteria, based on which they are classified into onshore, nearshore and offshore technologies. The type of power absorption method can be another criteria, where different systems are classified into point absorbers, attenuators, overtopping devices etc.

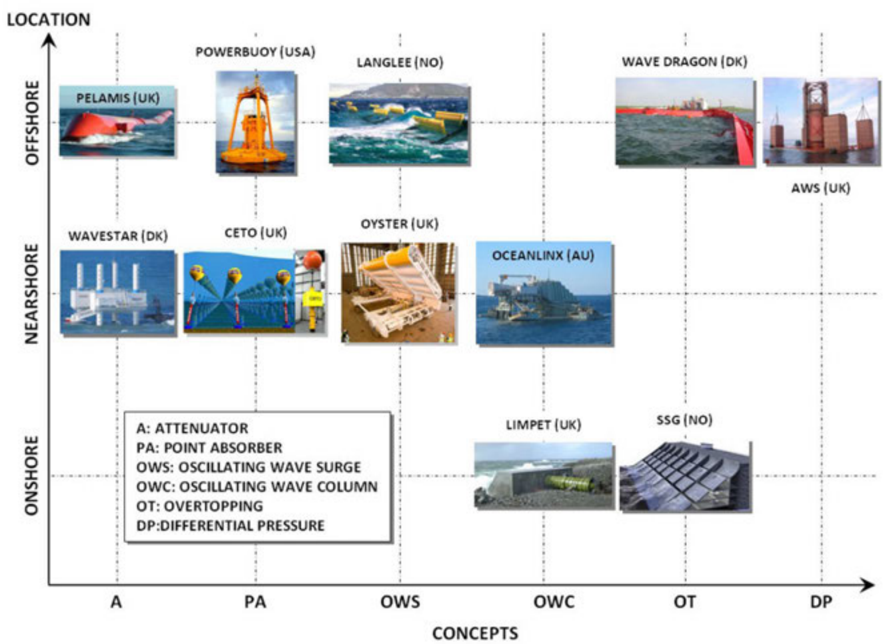


Figure 1.1 Wave energy extraction concepts and devices [5]

A cluster of numerous small units is always better when considering the failure impact. One of such initially developed systems, belongs to point absorber based wave energy converters [6]. The point absorbers, which float on the water surface, mainly have six degrees of freedom, but heave motion is dominant for most of the devices. The studies on the spatial distribution of these point absorbers shows that the distributed point absorbers can lower the power fluctuation compared to a single large system [7].

1.4 Uppsala University WEC concept

The WEC concept developed at Uppsala University is briefly presented in this Section. The Division of Electricity, Uppsala University, Sweden along with the spin-off company Seabased AB have developed a unique direct-driven point absorber type wave energy converter technology called Direct Drive Linear Permanent Magnet Generator (DDLPMG) for the wave energy extraction from the sea, using distributed point absorbers based farm concept [8], [9]. In this concept, mainly the kinetic energy in the heave motion of the point absorber/buoy is utilized for electricity generation. The underwater linear generator is placed on concreate foundation on the seabed as shown in Figure 1.2. The permanent magnets are mounted on the moving part of the generator, called translator, which is connected to the point absorber using a flexible steel rope. Due to the up-down motion of the translator along with the floating buoy, the magnetic flux linkage in the stator coil changes accordingly and also its sign when the translator travels each pole pitch. Thereby, an emf is produced in the stator winding. The generator output voltage varies in its magnitude and phase according to the translator-stator interaction which in turn results from the wave motion. The typical output voltage waveform of the LPMG can be found in Figure 2.1 with more details in Chapter 2. This technology is considered as the variable-renewable-energy (VRE) study reference, for the power electronic conversion system developed during this research project.

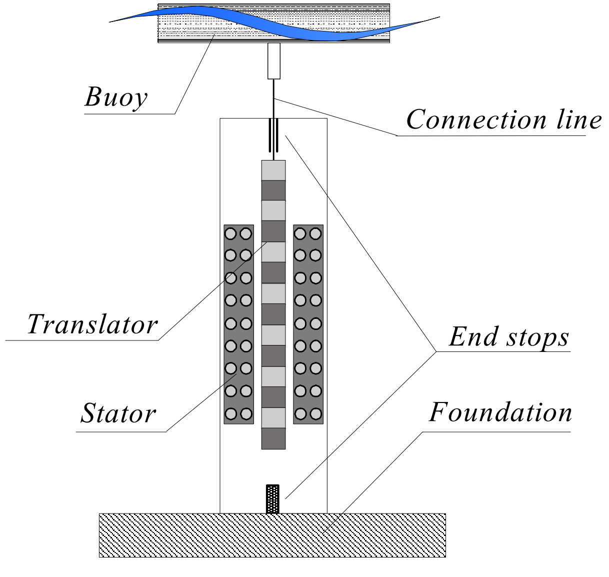


Figure 1.2 Direct drive linear permanent magnet generator

1.4.1 Previous works on the power electronic system

The wave energy research project at Uppsala University has a long history. Many PhD, licentiate and master theses have already been produced by the wave group. They belong to different areas covering several aspects of wave energy conversion ranging from hydrodynamics, mechanical system, environmental impact, electromagnetic design of generators, power electronics etc. A status update report of the research work done by Uppsala University researchers can be found in Paper X. Some of the previous PhD works related to the power converter system is listed below.

One of the early thesis discussing about various aspects of the electrical system was presented by K. Thorburn from 2006 [10]. C. Boström described first steps and future possibilities for converting electrical energy from the linear generator in her thesis from 2011 [11]. R. Krishna presented the first multilevel converter based grid interface system for the LPMG in 2014 [12]. R. Ekström described the development of an underwater marine substation with various power converter topologies in his thesis from 2014 [13]. Grid connection of permanent magnet generator based renewable energy systems and techniques are described by S. Apelfröjd in his thesis from 2016 [14].

1.5 Role of power electronics

Power electronics is the key technology which facilitates the conversion, conditioning and control of electric power flowing from source to load, with the help of power semiconductor switches and passive elements, while maintaining high conversion efficiency [15], [16]. Power electronic circuits are primarily used for processing energy. The goal of the power conversion system includes high efficiency conversion, system size reduction, weight and cost minimization, regulation of the output etc. Power converters can be mainly classified into four categories based on the type of their input and output: AC/DC, DC/AC, AC/AC and DC/DC converters.

A simplified block schematic of a typical power electronic conversion system used for renewable energy grid integration is shown in Figure 1.3. The main task of this power conversion system is to convert the varying electrical output from the renewable energy generators into a 50Hz/60Hz sinusoidal line frequency AC signal which can be interfaced to the utility grid by satisfying the grid codes. From Figure 1.3, it is also evident that the actual power conversion system is not only the power circuit with power semiconductor switches and passive components, but it also needs feedback sensors, digital/analog control circuits, gate drivers to control the switching, various filters to unwanted switching harmonics and in some cases galvanic isolation before grid connection.

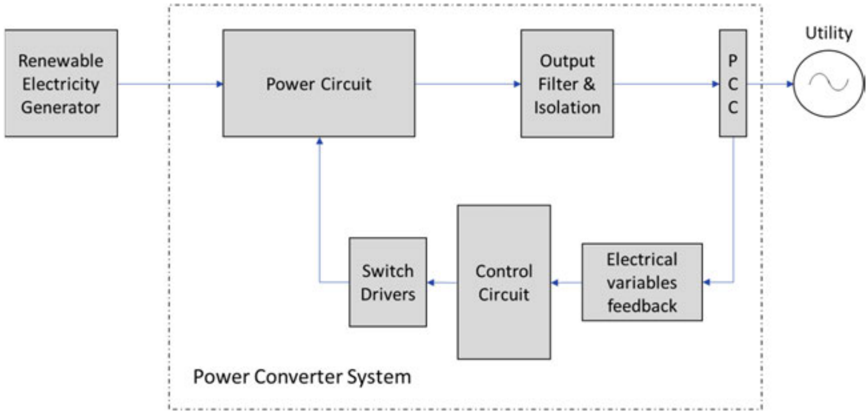


Figure 1.3 Simplified block schematic of renewable energy grid integration system. PCC is the point of common coupling where the system output connects to the grid.

The thesis mainly describes a multilevel multistage (with three power conversion stages – AC/DC, DC/DC and DC/AC) power converter system and control developed for the grid integration of wave energy converters. The following Chapters explain in detail various aspects of the converter system. Special power converters with embedded intelligence and large controllability range is beneficial for many future renewable energy conversion systems. Even though the power converter system developed during this research project is tuned for wave energy conversion and grid integration, it can be used for other VRE grid integration scenarios as well, with minor changes in the control strategies. More details can be found in Chapter 2.

1.6 Outline of the thesis

Chapter 2 gives an overview of the power conversion system. It also discusses the requirements, topologies and selection of the power converter system. The DC-link power conditioning is described in detail in Chapter 3. TLBC and TLBBC DC/DC converters and their control are included there. Chapter 4 mainly discusses the TLNPC based grid connection and control. Various interconnection strategies and their needs are listed in Chapter 5. Multilevel multistage converter system hardware development is described in Chapter 6. AC2AC Direct converter MMC development at Siemens is briefly described in Chapter 7. Important results and discussions are included in Chapter 8. Chapter 9 lists the conclusions from the work while Chapter 10 includes various future work descriptions. The summary of papers is included in Chapter 11.

2 Power conversion system: an overview

The Chapter gives an overview of the power electronic converter system developed during the research project. It explains the reasons for selecting each converter stage and the entire converter topology for grid connection of the wave energy converters.

2.1 Power converter requirements

Grid integration of any renewable energy source needs a power converter system which can produce a stable sinusoidal 50Hz/60Hz standard utility output voltage and current, irrespective of its input signal type, such as variable DC from solar PV, variable AC from wind generators etc. It must ensure that all the grid codes are satisfied when connecting the renewables to the grid. The WEC here as mentioned in the previous Chapter is a point absorber type direct driven linear machine without any hydraulics and gear system. That makes it

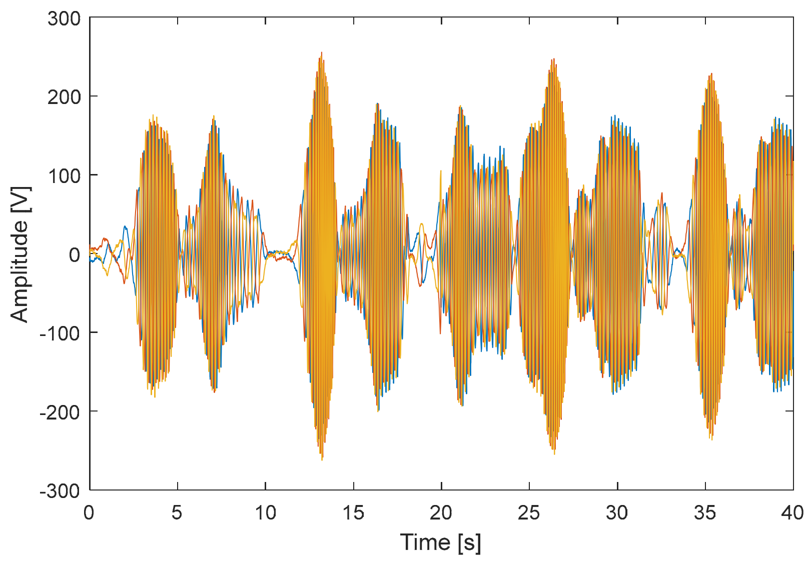


Figure 2.1 Typical output voltage wave form of a three-phase LPMG

a very simple, compact, efficient and cheap solution for the wave energy absorption. Due to the same reason, the generator electrical output reflects the exact random nature of the wave energy input as shown in Figure 2.1. Thus, the power conversion system must handle the high fluctuations in voltage, frequency and phase of the LPMG output and provide a stable sinusoidal standard utility output. Compared to the power conversion systems used for the grid integration of other VRE sources, the complexity and challenges here are much higher. For example, compared to the wind turbine with rotating machine and pitch angle control on its blades, the linear direct driven machine here, can only have electrical damping control, which is much more complex. In short, all the control challenges come to the power electronic system side rather than to the mechanical systems. Due to the same reason, it is advantageous to use a smart power converter system with embedded intelligence for efficiently grid connecting the WECs.

2.2 Converter topology selection scenario

Since the input to the power converter is a variable AC signal from the WEC output as shown in Figure 2.1 and the required output is the utility standard signal, the need for an AC/AC conversion system is obvious. There are several ways and topologies to achieve this objective. Most commonly a multistage power converter system is used for such applications, which consists of AC/DC (rectifier) converter as the first stage, a DC/DC converter in the middle and a DC/AC (inverter) at the final stage for facilitating the grid connection. The selection of power converter topology can also depend on a lot of other factors like input voltage and power levels, what kind of power transmission is required, how the WECs are interconnected, what kind of power absorption and controls are needed for the WECs, how large the DC-link storage capacity can be, what kind of underwater sea cable being available for transmitting power to shore, reliability and safety requirements for underwater operation, power quality requirements and last but least: efficiency and cost effectiveness of the converter system.

It is very clear from the above description that power converter system selection is a multivariable optimization problem and it is hard to suggest any unique solution for this. Different solutions depending on combinations of different practical scenarios need to be addressed in this case. For example, a single WEC grid integration (seldom required) may need a solution, but multiple WECs may need another kind of solution and a specially well distributed wave farm may need an entirely different power conversion approach. It is not only due to the obvious power level rise in the later cases, but it can be also due to many other factors like power fluctuation control by WEC interconnections and point absorbers' spatial distributions, variations in DC-link storage requirements, interactions between generators at the point of interconnection, damping control requirements etc. Since the wave farm is only at the research and development stage, it makes sense to consider a single WEC and multiple WEC grid connection scenarios at the beginning for choosing suitable power converter topologies. On a later stage, by scaling up the converter topology, the farm interconnection could be possible.

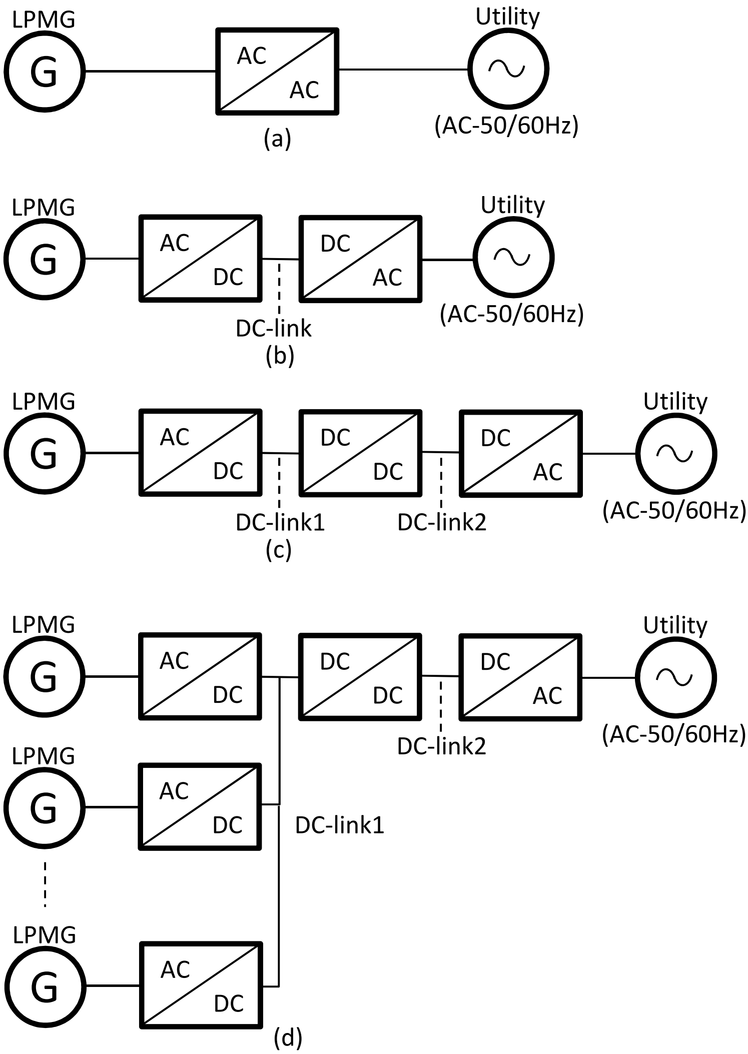


Figure 2.2 Various power conversion options

2.2.1 Different power conversion stages and options

Many possibilities and topologies exist when considering the type of power conversion system with different stages used for grid integration.

Figure *2.2* shows the simplified block schematics of various grid connection options. Figure *2.2* (a) shows a direct AC to AC conversion option which looks very compact for this purpose considering the single stage conversion option. The direct converter options are using advanced and complicated converter topologies. They are mostly in research phase now and the costs for such advanced multilevel converters are high at this stage to realize or test their potential for applications like WEC to grid integration. Chapter 7 describes an advanced AC2AC direct converter developed by Siemens AG and gives more insight to the future of such topologies.

Figure 2.2 (b) shows a typical rectifier and inverter based grid connection. Here, the DC-link is directly connected to the rectifier output. Large voltage ripple at the DC-link demands for large filter capacitors. Since WECs produce very low output at low wave conditions, DC output voltage from the rectifiers can become less than the minimum required DC-link voltage level necessary for grid connection. Thus, the configuration is not suitable for maximizing the utilization of the WEC-grid integration system.

The third configuration in Figure 2.2 (c) avoids the above problem by introducing a DC/DC boost converter stage after the rectifier. This ensures that DC-link2 always gets a well-regulated DC voltage with higher voltage level, for facilitating the grid connection even though the rectifier output might stay at low voltage level. This could improve the utilization of the system.

The last configuration shown in Figure 2.2 (d), is similar to the previous one, except, instead of considering a single WEC at the input, a number of WECs are used. Each WEC needs its own rectifier since interconnection of different WEC-rectifier units, is much easier at the DC-link1. Direct interconnection at the AC output terminals of WECs is much more difficult and requires additional components. The DC/DC and the DC/AC converters after the DC-link1 should be able to satisfy the high-energy conversion requirements due to multiple WECs' being connected to the system. The current work mainly uses the last two configurations as they are more suitable and reliable for the purpose. Chapter 5 gives more details about interconnection strategies.

2.2.2 Multilevel converter topologies

Power conversion stages presented in the last Section such as AC/DC, DC/DC and DC/AC converters can have different topologies serving the same purpose. Power converters can be classified into two-level converters and multilevel converters based on the number of voltage levels at the output of the converter. Multilevel converters have several advantages over their two-level counterparts and are getting popular for renewable energy conversion applications [17]. The thesis mainly deals with multilevel converter based WEC to grid integration system. More details are listed in the following Sections.

2.2.2.1 Advantages multilevel converters

Theoretically multilevel converters in general have the following advantages.

- Capability of high power conversion
- Permits power conversion at medium and high voltages
- Voltage stress, dv/dt, across each semiconductor switch remains low
- High quality staircase AC output compared to its two-level inverter counterpart, thus reduced filter requirements at the AC output
- Lower switching frequency and lower switching losses
- Better harmonic elimination capabilities
- Enhanced power quality, power flow control and efficiency for high power conversion

The thesis also shows special capabilities of multilevel converters suitable for VRE grid integration as described in the following Chapters.

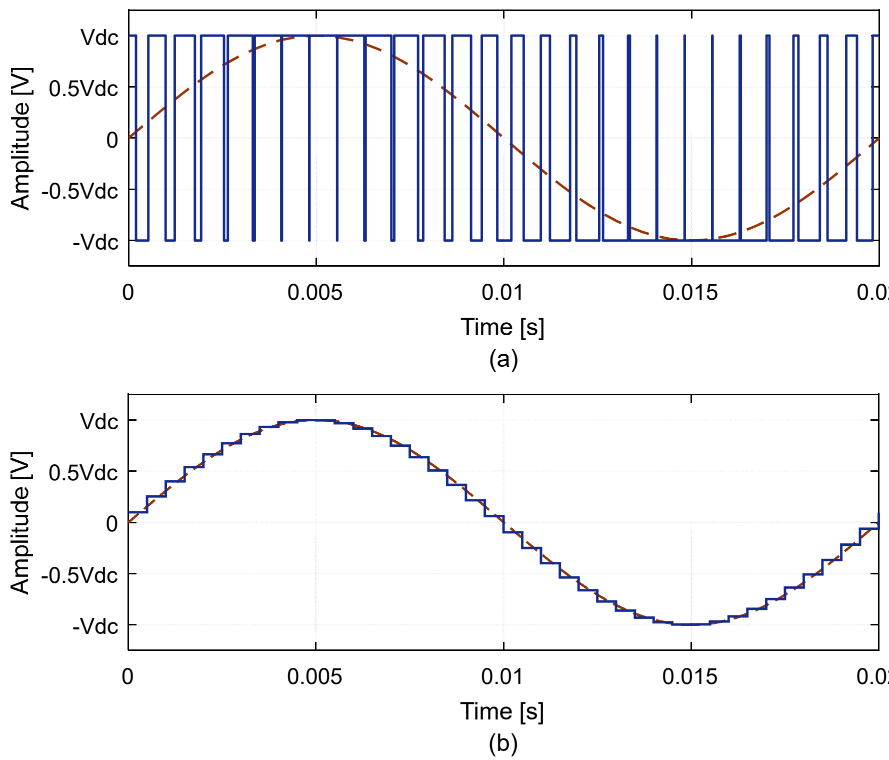


Figure 2.3 Two-level and multilevel inverter output voltage wave shapes - blue waveforms are the inverter outputs and brown dashed waveforms show the fundamental components (a) PWM voltage output from a two-level inverter (b) Staircase wave shape at a multilevel inverter output

2.2.2.2 Two-level and multilevel inverter outputs' comparison

The difference between a two-level voltage source PWM inverter output and a multilevel inverter output can be easily identified from Figure 2.3.

The output voltage is nearly sinusoidal from a multilevel inverter with sufficient number of levels. There are certain factors preventing the usage of multilevel inverters for all the power conversion applications.

2.2.2.3 Disadvantages of multilevel converters

Theoretically, multilevel converters in general have the following disadvantages. But their usage is a tradeoff between various factors and depends on the application scenarios.

- Large number of semiconductor switches required
- High cost compared to its two-level counter part
- Complexity of control increases largely
- Special capacitor voltage balancing/circulating current controls are required
- Some topologies may have unequal power dissipation among switches
- Some configurations need isolated input DC power supplies

Despite all the disadvantages, multilevel converters are getting highly popular in medium power and high power industrial applications, by overcoming most of the disadvantages using smart control techniques. For low voltage applications, the conventional two-level converters are still popular in the market manly due to their low cost and high reliability.

2.2.2.4 Types of multilevel converters

There are several topologies and classifications for multilevel converters based on various parameters as shown in Figure 2.4 [18]. Each topology or each structure has its own features which is one of the main selection criteria for an application by considering its fittingness for the purpose. Moreover, the cost effectiveness, efficiency, reliability etc. can also influence the selection process.

2.2.2.5 Selection of a topology for WECs to grid integration

Final selection of a multilevel topology for the WEC grid integration prototype was mainly based on the following factors.

- Power level of the system at which prototype needs to be tested
- WEC output wave shape and controllability challenges
- Voltage level at the DC-link and the ripple
- Single and multiple WECs availability for testing
- Cost-effectiveness of the solution
- Market availability of the IGBT modules
- Modularity and scalability for the future farm grid integration.

LPMGs are being upgraded over the years and the nominal power output is rated from 20kW in old generations to 80kW in new generations. Considering an availability of 3 generators rated 40kW each, at the beginning of the project, a possible power level for the system testing was 120kW. The generator output voltage at designed translator speed can be 210V in the old generations and 420V in the new generations. The actual voltage peaks from the generator, however can be much higher during large wave heights and becomes nearly zero at very low wave heights.

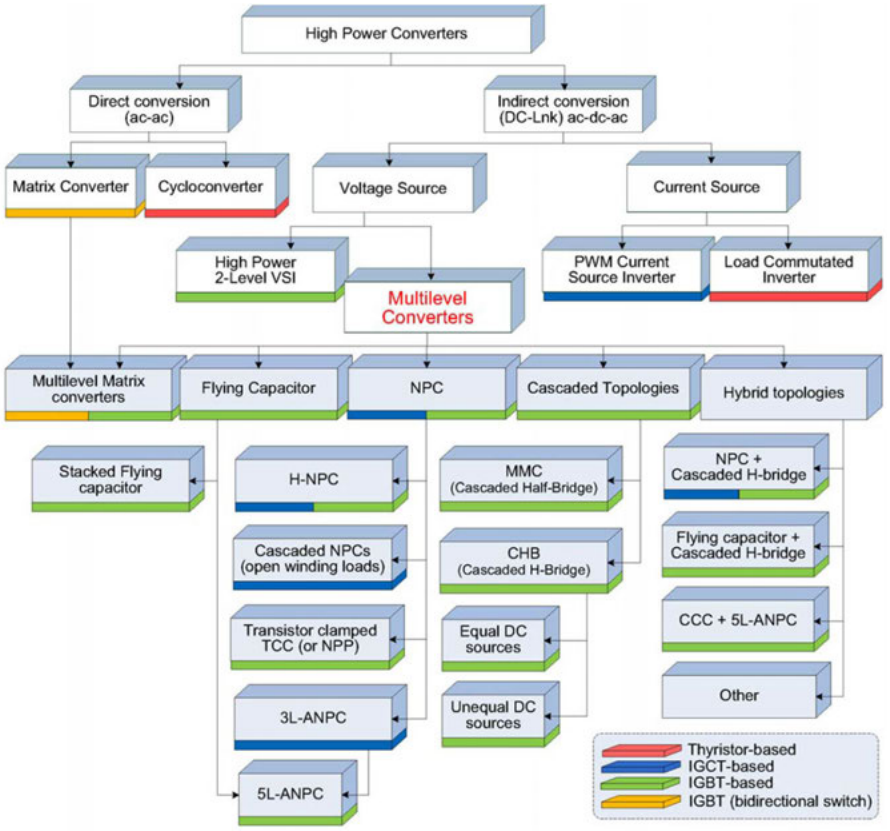


Figure 2.4 Classification of multilevel converters listed in [18]

2.3 Interconnection concepts

A definite interconnection concept decides the system viability for the total energy integration. The complete system can be configured in several ways. The optimal configuration depends on the cost, efficiency and redundancy measures. Since power fluctuations from the individual WECs are higher, the

interconnection of such units must be done in the early conversion stages, in such a way that it can reduce the fluctuations before going into the later stages. Otherwise, it leads to the need for overrated components. However, the interconnection at the AC side requires a large number of low frequency transformers which is usually not a preferable or cost-effective solution.
A much better approach is to interconnect the generator-rectifier units at the DC side, facilitating the accumulation of energy in a common DC-link. This approach helps to minimize fluctuations in the DC-link, as a number of generators increases. Chapter 5 details various interconnection strategies for the WEC-rectifier units.

2.4 Final selection of multilevel multistage converter topology

Based on various factors and scenarios listed in this Chapter, a suitable converter system has been selected for the WECs to grid integration after extensive simulation studies. Since the aim of the research is to develop a future smart converter system suitable for wave energy conversion, the research does not include the conventional two-level converter based solutions, which are already tested by previous researchers to identify its advantages and limits for the wave energy conversion.

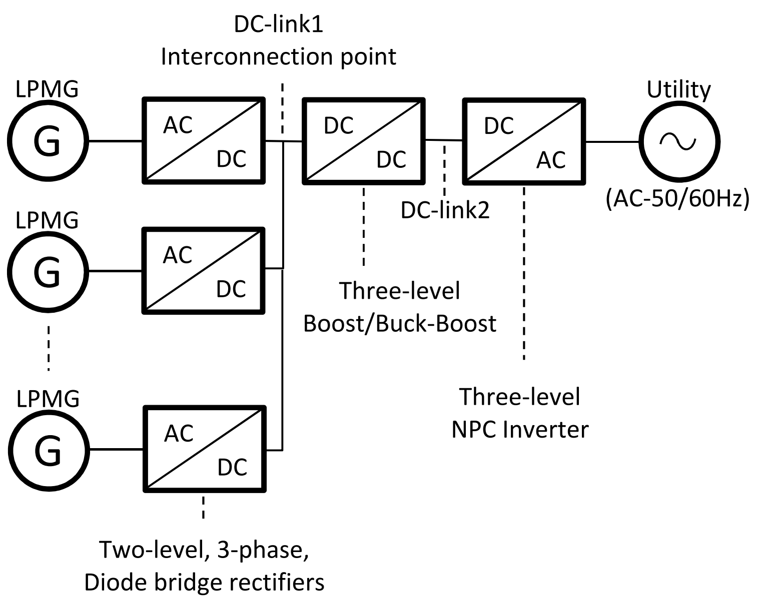


Figure 2.5 Multilevel multistage converter system developed for the WECs to grid interconnection.

The current work develops power converter solutions starting from the electrical system input side (LPMG output) to the grid connection side. WEC-diode rectifier units are interconnected to form the DC-link1. Three-phase diode bridge rectifiers are used for the purpose. Even though they are uncontrolled rectifiers, the attention is given to the interconnection strategies to form a stable DC-link1. The focus is given to DC-link power conditioning to form DC-link2 where three-level boost converter (TLBC)/three-level buck-boost converter (TLBBC) with smart control techniques are used. The final grid coupling stage is designed using a three-level neutral point clamped (TLNPC) inverter where several improvements are also incorporated compared to conventional grid tied system. The final system block schematic is shown in Figure 2.5. Multilevel multistage converter system with field programmable control and communication makes the entire system more flexible, controllable and future smart grid compatible.

When features like customizable control intelligence, communication interface and field programmability are combined into the power converter control system, the converter can be called a smart power converter.

3 DC-link power conditioning

The DC-link power conditioning is the foremost requirement in any VRE grid integration system. In this Chapter, the focus is given for the DC-link converters which facilitate the power conditioning in an efficient way. The Chapter is based on Papers I to V.

The DC/DC converters are selected and designed based on the assumption that the grid coupling is done based on a TLNPC inverter, as explained in Section 2.4. These converters exist between the rectifiers and the inverter in the multistage power conversion system as shown in Figure 3.1. The details about three-level inverter, modulation strategies and grid connection controls are described in Chapter 4. This Chapter includes a detailed description of different multilevel DC/DC converter configurations and controls used for the DC-link power conditioning for a multistage power conversion system. The input voltage balancing of the NPC inverter using DC/DC converter is also detailed in this Chapter.

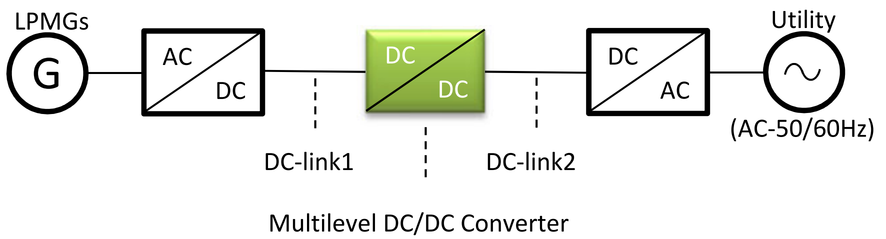


Figure 3.1 Multilevel DC/DC converter between rectifiers and inverter

3.1 Requirements and scope

The primary requirement for the DC-link power conditioning is due to the high variation in the DC-link input from VRE converters like DDWECs as explained in Section 2.1. A stable DC-link is an essential requirement for any reliable renewable power conversion system. A converter with wide controllability range is essential for this. Second demand is for a converter with large voltage boosting capability which can support the system operation at low wave climate as well. Voltage step-down can also help the operation at high wave climate, but it is not so much significant compared to voltage boosting as the WEC system should be shut down at large wave climate to prevent any damage to the WECs' mechanical system. Thus, large range DC voltage amplification or suppression at the DC-link2 can help to improve the entire system utilization and efficiency.

The configuration of this intermediate converter is also depending on the grid side converter. Most of the multilevel topologies belonging to the NPC family has the disadvantage of voltage unbalance between the DC-link capacitors. There are several conventional voltage balancing techniques based on various modulation strategies to cross regulate the capacitor voltages at the DC-link [19]–[21]. These techniques have limits in their voltage balancing capabilities and won't be sufficient for a wide operating range. Hence three-level NPC inverter based grid coupling demands for a suitable DC/DC multilevel converter for capacitor voltage cross regulation at its DC-link input. This can ensure that the DC/DC converter also support operation at higher voltage.

For the submerged DDLPMG explained in the Section1.4, The DC-link voltage regulation can be used for the damping control. The DC-link voltage based passive damping eliminate the sensor requirement for the damping control. However, it increases the voltage stress in the DC-link. Therefore, an additional conversion stage is required to handle these ripples in voltage and current.

The topology selection of the DC/DC converter is done based on all the above requirements and demands. TLBC is mainly used for the DC-link power conditioning while the possibility of using TLBBC is also verified.

3.2 Three-level boost converter

The conventional boost converter is a popular topology for DC-link voltage regulation for renewable energy conversion and for a lot of other industrial applications. The application of boost converter for a two-level inverter based WEC grid connection system is detailed in [22]. Three-level NPC inverter based medium power grid connection system needs an enhanced DC/DC converter with higher controllability range and better cross regulation capabilities as explained in the previous Section. A TLBC is proposed for this purpose in Paper I and Paper II.

3.2.1 TLBC topology

In Papers I and II, state of the art for the three-level converter topologies are presented briefly. These papers present circuit design, all the cases of operation, pulse delay control design, simulation and experimental results. The basic circuit of TLBC and modes of operation are shown in *Figure 3.2* and Figure 3.3. The converter also known as single input dual output (SIDO) boost converter because of its circuit structure. It can produce three DC voltage levels at the output, hence given the name TLBC. In TLBC, the voltage stress across the switches is half, compared to that in the conventional boost converter.

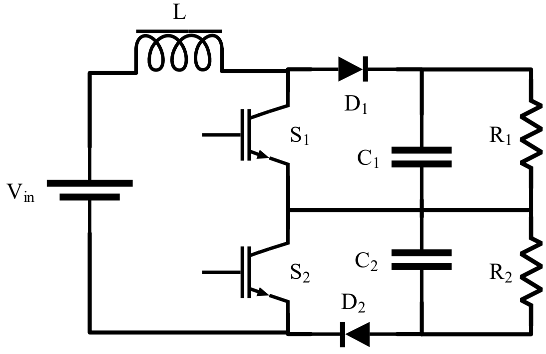


Figure 3.2 Basic circuit schematic of the Three-level boost converter

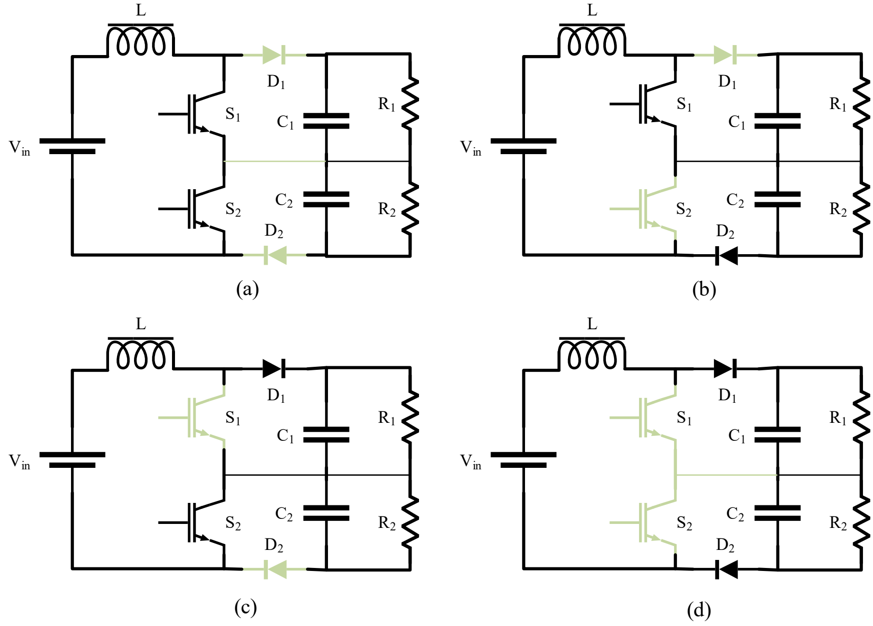


Figure 3.3 Four modes of operation of a TLBC (a) mode1, (b) mode2, (c) mode3, (d) mode4

3.2.2 Basic operational modes of a TLBC

The boost converter allows four different modes of operation. TLBC output characteristics depends on the timing and sequencing of these switching modes. It is assumed that the inductance L is large enough to maintain the current in continuous conduction mode (CCM) and the capacitors are large enough to keep the output voltage constant. The four modes of operation of boost converter in steady state with relevant voltage and current equations are given below.

In mode 1, both S_1 and S_2 are ON. Therefore, the inductor current increases and the load current is supplied by C_1 and C_2 as shown in Figure 3.3(a). The relevant voltage and current equations during this interval is given in (3.1).

$$pi_L = \frac{v_{in}}{L}; \quad pv_{C1} = -\frac{v_{C1}}{R_1C_1}; \quad pv_{C2} = -\frac{v_{C2}}{R_2C_2} \tag{3.1}$$

where p is the differential operator d/dt. v_{in} is the input voltage, v_{C1}, v_{C2} represent the corresponding voltages across C_1 and C_2, i_L is the inductor current and R_1, R_2 are the load resistors.

In mode 2, S_1 is ON and S_2 is OFF. Therefore, the capacitor C_2 charges and the capacitor C_1 discharges to the load as shown in Figure 3.3(b). The state equations in this mode are presented in (3.2).

$$pi_L = \frac{v_{in} - v_{C2}}{L}; \quad pv_{C1} = -\frac{v_{C1}}{R_1C_1}; \quad pv_{C2} = \frac{i_LR_2 - v_{C2}}{R_2C_2} \tag{3.2}$$

In mode 3, S_1 is OFF and the switch S_2 is ON. The input current flows only through the first output (C_1 and R_1) and current through R_2 is supplied by the capacitor C_2 as shown in Figure 3.3 (c). Voltage and current equations during this interval are listed in (3.3)

$$pi_L = \frac{v_{in} - v_{C1}}{L}; \quad pv_{C1} = \frac{i_LR_1 - v_{C1}}{R_1C_1}; \quad pv_{C2} = -\frac{v_{C2}}{R_2C_2} \tag{3.3}$$

In mode 4, both S1 and S2 are OFF as shown in Figure 3.3 (d). The input current flows through both outputs and delivers energy. The state equations can be expressed as in (3.4).

$$\begin{gathered} pi_L = \frac{v_{in} - v_{C1} - v_{C2}}{L}; \quad pv_{C1} = \frac{i_LR_1 - v_{C1}}{R_1C_1}; \\ pv_{C2} = \frac{i_LR_2 - v_{C2}}{R_2C_2} \end{gathered} \tag{3.4}$$

From the above equations, it is clear that mode 1 and mode 4 corresponds to the conventional boost converter operation. When combined with mode 2 and mode 3, TLBC converter exhibits superior output performance, which is explained in the following Sections.

3.2.3 Control of TLBC

Details of control design is explained in paper I and paper II. The pulse delay ratio (λ) is defined as (*3.5*).

$$\lambda = \frac{\text{delay between Gs1 and Gs2}}{\text{T}} \tag{3.5}$$

Where Gs1 and Gs2 are the gate drive signals of switches S_1 and S_2 respectively. Depending on the value of duty ratio d and pulse delay ratio λ, the TLBC converter operates in ten different cases which are shown in Table 3.1.

Case	Mode sequence
I	Mode 1 ⇒ Mode 4
II	Mode 1 ⇒ Mode 3 ⇒ Mode 4⇒ Mode 2
III	Mode 1 ⇒ Mode 2 ⇒ Mode 4⇒ Mode 3
IV	Mode 2 ⇒ Mode 3
V	Mode 1 ⇒ Mode 2 ⇒ Mode 3
VI	Mode 1 ⇒ Mode 3 ⇒ Mode 1⇒ Mode 2
VII	Mode 1 ⇒ Mode 3 ⇒ Mode 2
VIII	Mode 2 ⇒ Mode 4 ⇒ Mode 3
IX	Mode 2 ⇒ Mode 4 ⇒ Mode 3⇒ Mode 4
X	Mode 2 ⇒ Mode 3 ⇒ Mode 4

Table 3.1 Operative cases of a TLBC

Duty ratio control is used for the voltage boost control and PDC method is used for the cross regulation. Combining these two techniques in a smart way facilitates enhanced features at the TLBC output. That means, different cases exhibit different output characteristics and by controlling the cases effectively can control the converter output performance. In order to make the analysis clear, three operating regions of the converter can be defined based on the d values when d=0.5, when d>0.5 and when d<0.5, as shown in Figure 3.4.

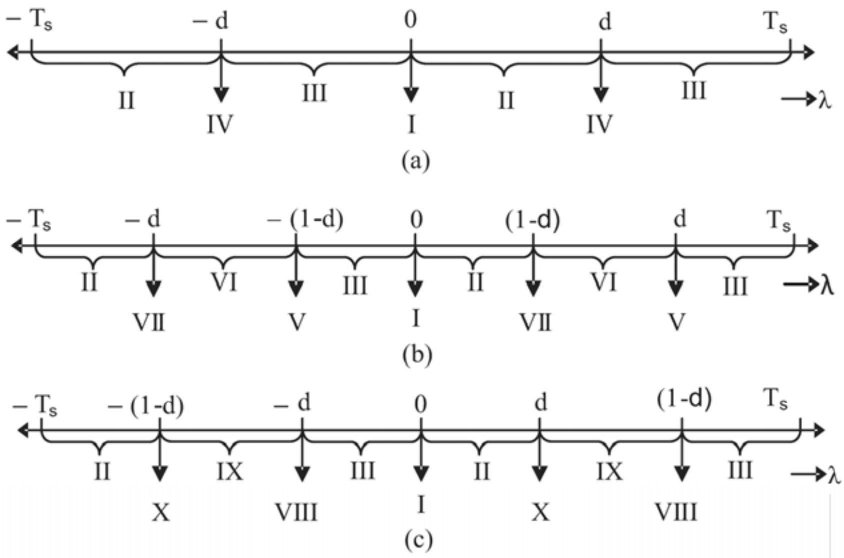


Figure 3.4 Operational cases of TLBC in terms of duty ratio and pulse delay ratio (a) when d = 0.5, (b) when d > 0.5 and (c) when d<0.5.

3.2.3.1 Ripple current based state space averaging method

The parameter identification for total DC-link voltage regulation is similar to the conventional boost converter using classical state space averaging technique. The transfer function between output voltage to duty ratio for case II can be simplified into G_1(s).

$$G_1(s) = \frac{-I_L}{C(s + (2/RC))} \tag{3.6}$$

In contrast, the conventional state space averaging technique may not be useful for designing the voltage imbalance regulator as the ripple in the inductor cannot be ignored. Inductor current ripple based state space averaging method is used for deriving the system transfer function and also for the controller design. For example, the voltage imbalance cross-regulator design outline for case II is given below. The corresponding case II waveforms can be found in Figure 3.5.

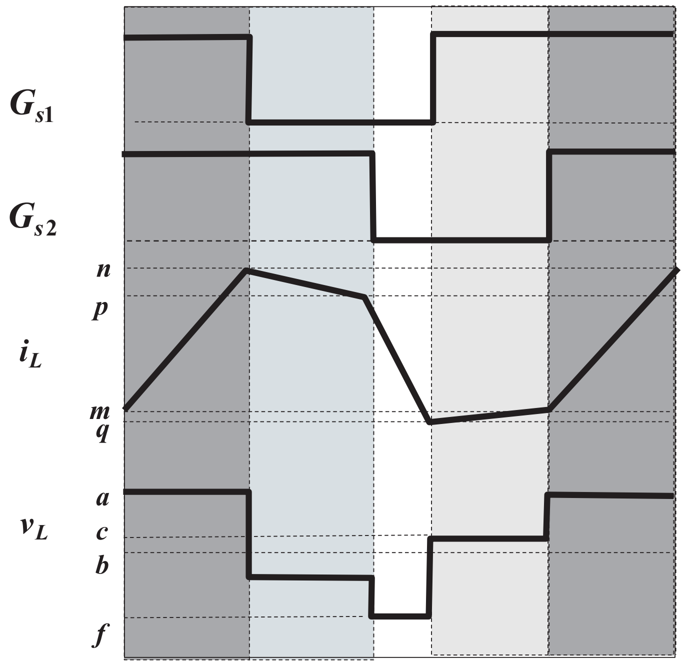


Figure 3.5 Gate signals G_{S1} and G_{S2}, inductor current i_L and inductor voltage v_L of TLBC

The inductor current ripple levels are denoted by m, n, p and q. Mode 1 to Mode 4 switching times are denoted by d_1 to d_4 respectively. The ripple current averaging can be denoted by (3.7).

$$i_L = \frac{(m+n)}{2}d_1 + \frac{(n+p)}{2}d_3 + \frac{(p+q)}{2}d_4 + \frac{(q+m)}{2}d_2 \quad (3.7)$$

In general, the system representation in state space form is $\dot{x} = \boldsymbol{A}x + \boldsymbol{B}u$. The state variable matrix x is chosen as $[i_L\ v_{C1}\ v_{C2}]^T$; u is the input variable v_{in}. From the inductor current ripple based averaging technique, the state matrix A and input matrix B can be calculated as follows

$$\begin{aligned} A &= a_1 d_1 + a_2 d_2 + a_3 d_3 + a_4 d_4 \\ B &= b_1 d_1 + b_2 d_2 + b_3 d_3 + b_4 d_4 \end{aligned} \quad (3.8)$$

After substituting and deriving to find A and B as explained in Paper II, the following expressions are obtained.

$$A = \begin{bmatrix} 0 & \frac{d-1}{L} & \frac{d-1}{L} \\ \frac{1-d}{C_1} & \frac{-(d-\lambda)(1-d)^2 T}{2LC_1} - \frac{1}{R_1 C_1} & \frac{(1-d-\lambda)(d^2-d+\lambda)T}{2LC_1} \\ \frac{1-d}{C_1} & \frac{-[(d-\lambda)(1-d)^2+\lambda(1-d-\lambda)]T}{2LC_2} & \frac{-d(1-d)(1-d-\lambda)T}{2LC_2} - \frac{1}{R_2 C_2} \end{bmatrix} \quad (3.9)$$

$$B = \begin{bmatrix} \frac{1}{L} \\ \frac{(d-\lambda)(1-d)T}{2LC_1} \\ \frac{d(1-d-\lambda)T}{2LC_2} \end{bmatrix} \quad (3.10)$$

The expressions for neutral point voltage from DC and AC analysis can be derived by perturbation method and the final equations are listed below.

$$V_{np} = \left[\left(\frac{1-d-\lambda}{1-d}\right) + 2d - 1\right]\frac{\lambda RT}{2L}V_{in} \quad (3.11)$$

$$\tilde{v}_{np}(s) = \tilde{\lambda}(s)\frac{[(1-d-2\lambda)V_o + (2d-1)V_{in}]T}{2LC(s + (\frac{1}{RC}))} \quad (3.12)$$

By the above averaging method, the transfer function between neutral voltage and pulse delay ratio can be derived. By combining this with controller transfer function, the closed loop system transfer function is obtained. From this PI controller parameters can be calculated. Simulation and hardware test results are presented in Chapter 8.

3.2.3.2 SSPDC and PDC methods

Most of the conventional control methods for TLBC described already in the literature had many limitations. One of the important method in the literature is switch signal phase delay control (SSPDC) where the signal phase delay lies between d and (1 − d) for a duty ratio d [23]. The maximum and minimum value of normalized V_{np} by SSPDC method is 0.2102 (at d = 0.7 and λ = 0.015) and −0.1875 (at d = 0.3 and λ = 0.365). In the new pulse delay control (PDC) method, V_{np} varies from −0.3945 (at d = 0.5 and λ = 0.25) to 0.3945 (at d = 0.5 and λ = 0.75). PDC method provides extra controllability for the converter and thereby, improves the overall performance of the system.

3.2.4 Continuous and discontinuous modes of operation

The above analysis of TLBC and the controller design is based on the assumption that the converter always operates in the continuous current mode (CCM) of inductor current. Even though the PDC during CCM itself provides better flexibility and higher controllability compared to conventional method, the discontinuous current mode (DCM) of TLBC is also analyzed to evaluate its performance. Paper III describes the performance of DCM using simulations and compares with the performance during CCM. The voltage balancing capabilities of TLBC during CCM and DCM are shown in Figure 3.6 and Figure 3.7 respectively.

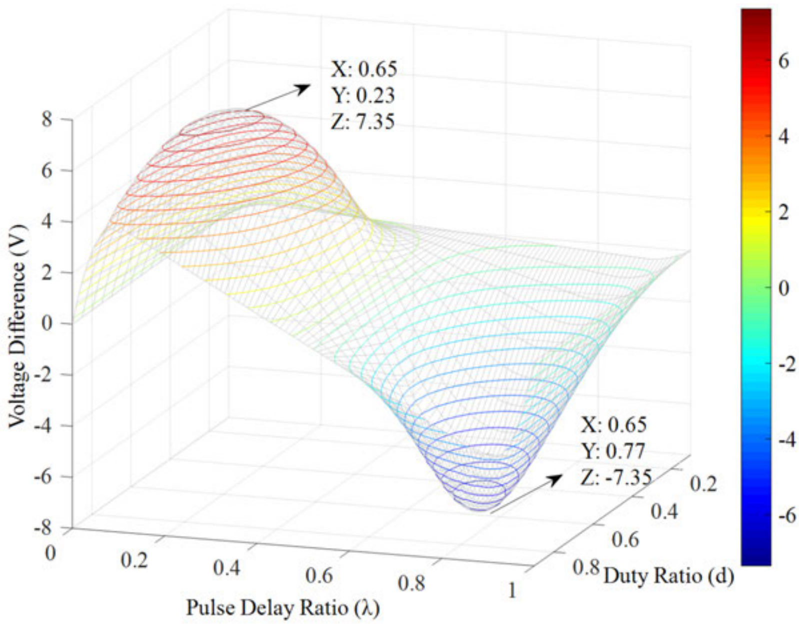


Figure 3.6 Voltage cross regulation capability of a TLBC converter using CCM

Identical circuits and parameters are used for the simulation of both CCM and DCM based testing of PDC in TLBC except the value of inductance used for the DCM test was only $1/8^{th}$ compared to the inductance value used during CCM based testing. Peak voltage unbalance shown during DCM is 58.5V compared to 7.35V during CCM. Thus, DCM can extend the range of unbalance compensation around 8 times compared to the CCM capabilities, in theory. Even though DCM looks really attractive in this aspect, there are several practical concerns when using DCM. The DCM has to produce very large current ripple in the inductor to maintain its output at the desired level. Even though the inductance value required is very less, the current peaks through the inductance are very high. This can make some practical limitations while winding the inductor coil. The conductors of the inductor coil should be of higher thickness to allow such large current peaks.

The controller design for CCM operation is much simpler compared to that of the DCM operation considering the fact that the CCM can only go through its 8 definitive cases during its cross-regulation operation. Whereas the DCM mode introduces non-predetermined delays with zero inductor current modes (segments), which complicates the controller design compered to CCM. Moreover, DCM cases of operation also makes some cases in CCM mode during its operation, due to its ripple current amplitude variations in each mode during each case. The controller gains are different during DCM and CCM and therefore online gain adjustment mechanism is needed in this regard, which in turn will increase controller complexity a lot.

Therefore, CCM is recommended over DCM for the applications which require high dynamic stability, even though the DCM capabilities are much wider. Whereas new DCM controller design methods should be investigated more thoroughly in order simplify the design process, to realize a reliable control technique.

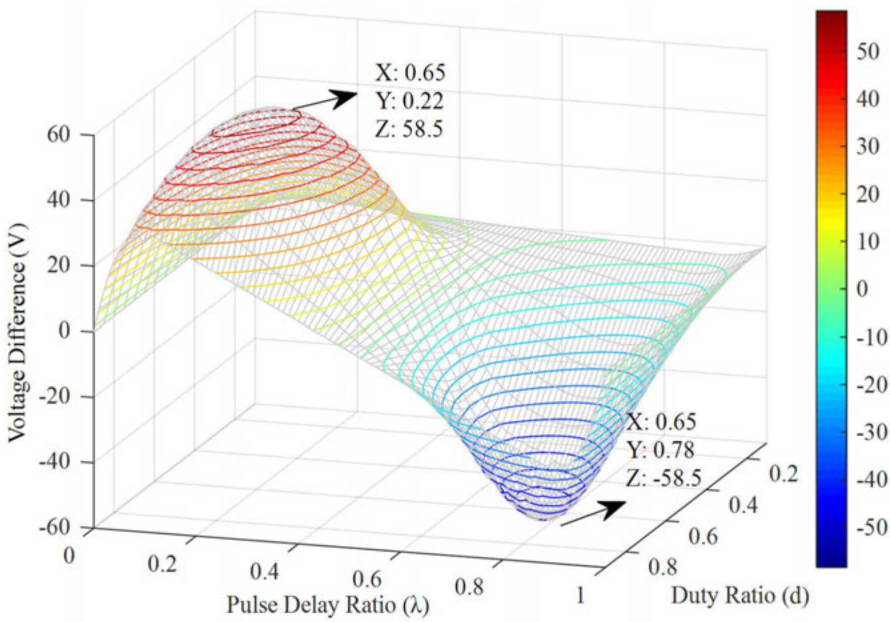


Figure 3.7 Voltage cross regulation capability of a TLBC converter using DCM

3.2.5 Experimental setup of TLBC

An experimental prototype of TLBC converter is implemented in the laboratory after the successful design and simulation stages. Figure 3.8 shows the first prototype of TLBC converter.

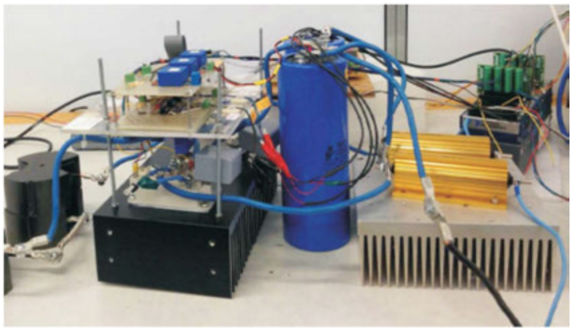


Figure 3.8 Experimental prototype of TLBC with NI CompactRIO – Virtex 5 FPGA and Labview based control system.

Two Semikron SKM 300GB063D Insulated Gate Bipolar Transistor (IGBT) modules are used as the main switches of TLBC. Each module has two IGBTs and two anti-parallel diodes. One IGBT with its anti-parallel diode and a second anti-parallel from the other IGBT are utilized from each module to realize the TLBC circuit. This optimizes the space and cost requirements while satisfying the TLBC diode performance needs. A dual channel gate driver, Concept 2SC0108T2A0-17 mounted on the evaluation board 2BB0108T2A0-17, is used to drive the two IGBT switches. High frequency inductor cores with ferrite material, PM114/93-3C90 are used with manual winding to make the inductor needed for the converter. Summary of component specifications and types are given in Table 3.2

Component / Parameter	**Type / Specification**
IGBT	SKM 300GB063D - IGBT
Diode	SKM 300GB063D - Diode
Inductor Core	PM114/93-3C90
Capacitor (C)	17 mF
Inductor (L)	131.5 uH
Load Resistor (R)	7.8 Ω
Snubber Resistor (R_S)	2.5 W
Snubber Capacitor (C_S)	3.3 uF
Switching frequency (F_{SW})	5 kHz
Sampling frequency (F_S)	25 kHz

Table 3.2 Component and parameter specifications for the TLBC prototype

First prototype is implemented as a standalone prototype without NPC inverter stage. Duty-ratio control and PDC are tested in this hardware after programming using Labview. The real-time closed loop control system is implemented using NI Compact RIO hardware, especially utilizing the Virtex-5 FPGA inside the CompactRIO.

3.3 Three-level buck-boost converter

This Section is based mainly on Papers IV and V. After analyzing the superior capabilities of TLBC converter for the voltage cross regulation applications like three-level NPC based VRE grid integration, it is of high interest to analyze the capabilities of TLBBC for similar purposes. Due to its voltage step-up and step-down capabilities, TLBBC can even increase the system utilization considering the widely varying input from renewable energy sources. Paper IV analyses the TLBBC circuit, modes of operation, cross regulation capabilities etc. in order to provide an insight in this regard. In Paper V further analysis, closed-loop controller design and simulation and experimental test results along with comparison of TLBBC and TLBC are presented.

3.3.1 TLBBC topology and operational modes

Compared to the Single Input Dual Output (SIDO) structure of TLBC, the TLBBC has a Dual Input Dual Output (DIDO) structure. It requires two input energy sources and has balancing and buck-boost capabilities at its dual outputs. The basic TLBBC circuit topology is shown in Figure 3.9. For renewable energy conversion, the TLBBC converter has many advantages compared to other two-level DC-DC converters. They can either step-up or

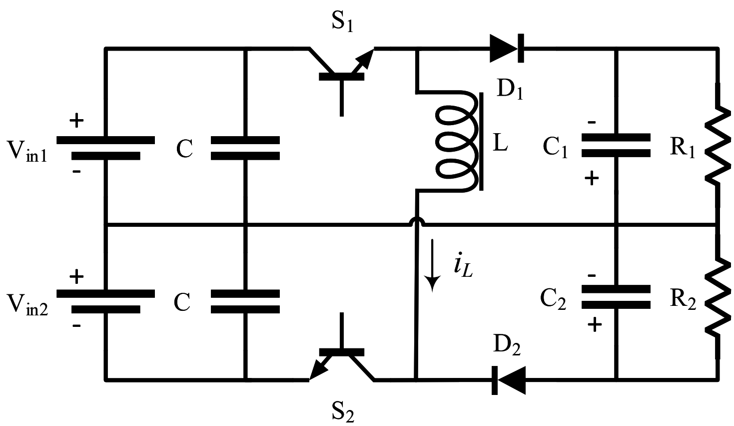


Figure 3.9 Basic circuit topology of a DIDO TLBBC

step-down the input voltage at high power levels depending on the power generated and power demanded. There will be an imbalance between the capacitor voltages when an NPC inverter is used to grid connect the TLBBC output. Active balancing can improve the controllability range of the entire grid connected system, similar to the PDC technique explained for the TLBC in the previous sections.

The TLBBC converter has also 4 main operational modes similar to TLBC converter as shown in Figure 3.10. The modes 1 and 4 corresponds to the normal buck-boost operation similar to the conventional buck-boost converter. Whereas, modes 2 and 3 corresponds to the balancing operation/cross-regulation. Each modes and corresponding state equations are listed in Paper IV.

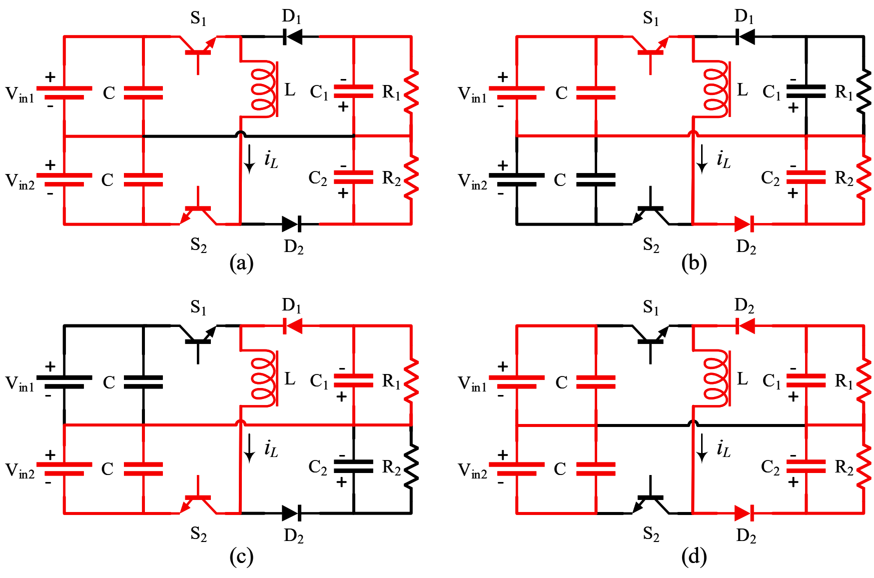


Figure 3.10 TLBBC circuit with four operating modes based on the switching states of the switches S_1 and S_2, defined as mode1 to mode 4: (a) Mode1: S_1 and S_2 ON, (b) Mode2: S_1 ON and S_2 OFF, (c) Mode3: S_1 OFF and S_2 ON, (d) Mode4: S_1 and S_2 OFF.

3.3.2 Operational cases and open-loop control equations

From the detailed analysis of TLBBC operation using different combination, sequencing and timing of TLBBC operating modes, it is found that the converter can go through 10 different operational cases during its entire range of operation similar to TLBC as shown in Table 3.3. The analysis is based on the assumption that the converter stays in continuous current mode (CCM) during all the cases of operation. These cases can be used for the numerical modeling of the DC-link voltage and thereby enable the design of the controller. The inductor ripple current is different in each case. So, the conventional state space averaging technique cannot be applied to all the cases. The inductor ripple current averaging technique with state space averaging method is the best suited one. Using this method, the capacitor voltage difference ΔV for each case is modeled. Table 3.3 also gives the expression of ΔV for all ten cases of operation of the TLBBC.

Cases	Mode sequencing	ΔV
I	mode1 → mode4	0
II	mode1 → mode3 → mode4 → mode2	$-\lambda[\lambda - 2d(1-d)]\Theta$
III	mode1 → mode2 → mode4 → mode3	$(1-\lambda)(2d(d-1)+1-\lambda)\Theta$
IV	mode2 → mode3	0
V	mode1 → mode2 → mode3	$-(2d-1)(1-d)^2\Theta$
VI	mode1 → mode3 → mode1 → mode2	$(2\lambda-1)(1-d)^2\Theta$
VII	mode1 → mode3 → mode2	$-\lambda^2(1-2\lambda)\Theta$
VIII	mode2 → mode4 → mode3	$(1-2\lambda)(1-\lambda)^2\Theta$
IX	mode2 → mode4 → mode3 → mode4	$(1-2\lambda)d^2\Theta$
X	mode2 → mode3 → mode4	$\lambda^2(1-d-\lambda)\Theta$

Table 3.3 TLBBC Operational cases and expressions for neutral voltage

Where d is the duty ratio of the switches, λ is the pulse delay ratio (delay between switch gate pulses/switching period) and Θ is a function of input and output voltages which is defined in (3.13).

$$\Theta = \frac{RT_s}{2L}[v_{C1} + v_{C2} + V_{in1} + V_{in2}] \tag{3.13}$$

3.3.3 Closed-loop controller modelling

The DC-link voltage regulation is carried out by using the buck-boost capability of the system similar to the conventional buck-boost converter control. The steady state output voltage, V_0 of the buck-boost converter can be calculated using the input voltage, V_{in} and the duty ratio, d, as shown in (3.14). Depending on the value of d, the converter either increases or decreases the voltage given to the input to derive the output voltage.

$$V_0 = V_{in}\frac{d}{(1-d)} \tag{3.14}$$

To get the desired output voltage for a varying source voltage, the duty ratio must be controlled. The PI controller computes the value of duty ratio, d required for achieving the desired output voltage. The equation of the controller for voltage regulation is given by (3.15).

$$d = k_{p1}e_v + k_{i1}\int e_v dt \tag{3.15}$$

where k_{p1} and k_{i1} are the proportional and integral controller parameters, and the error, $e_v = V_{ref} - V_0$; V_{ref} is the desired DC-link voltage and V_0 is the actual output voltage.

The voltage deference between the output capacitors, ΔV is sensed and is used in a PI controller to calculate a pulse delay ratio, as sown in (3.16). This delay is given to one of the switch pulse signal to move it either forward or backward with respect to the other pulse signal in order to compensate for the neutral point voltage.

$$\lambda = k_{p2}e_{\Delta v} + k_{i2}\int e_{\Delta v} dt \tag{3.16}$$

Where k_{p2} and k_{i2} are the PI controller parameters, $e_{\Delta v} = \Delta V_{ref} - \Delta V$.

Applying perturbations to the state variables, the expression of the neutral point voltage for AC analysis can be formulated. Considering case 2 for illustration, the system transfer function is given as shown in (3.17)

$$G = \frac{\widetilde{\Delta V}}{\lambda} = \frac{[2d(1-d) - 2\lambda]\, V_{in}T}{2(1-d)LC\left(s + \frac{1}{RC}\right)} \tag{3.17}$$

where T is the switching period. Since PI controller is used, the closed loop transfer function Gc is given by (3.18).

$$G_c = \left(k_{p2} + \frac{k_{i2}}{s}\right)\frac{[2d(1-d) - 2\lambda]\, V_{in}T}{2(1-d)LC\left(s + \frac{1}{RC}\right)} \tag{3.18}$$

To find the value of k_{p2} and k_{i2}, equate the characteristic equation in (3.18) to zero. The controller can be tuned using these values. For example, in case II, the values of k_{p2} and k_{i2} are 0.1596 and 33.9605, respectively. It is observed that the same value of k_{p2} and k_{i2} satisfies other cases of the operation of the TLBBC as well.

3.3.4 Hardware prototype of TLBBC

A hardware prototype of TLBBC is constructed in the laboratory test its practical feasibility and to validate the simulations. The hardware has similar component types of TLBC experimental setup but of different ratings. All the control strategies are tested on this hardware to check the performance of the converter. The NPC inverter coupling of TLBBC is not performed at this stage but expected to utilize this capability in the future projects, with specific requirements for this.

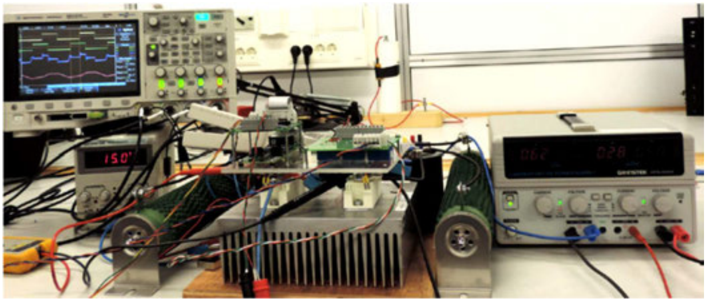


Figure 3.11 Hardware prototype of a TLBBC converter

4 Inverters and grid connection

In this Chapter, the inverter system used for grid coupling the WECs is described along with its control strategies. The Chapter is mainly based on Papers VI and VII.

Two-level inverters are still used in many industrial applications presently. In general, they have many limitations like limited voltage and power levels, large filter size, high dv/dt across its switches etc. Usage of a multilevel inverter for the renewable energy grid coupling application can be beneficial in many ways as described in 2.2.2. In the current work, a TLNPC is used for grid coupling of the WEC system. The position of TLNPC in the WEC-grid interface is highlighted in Figure 4.1.

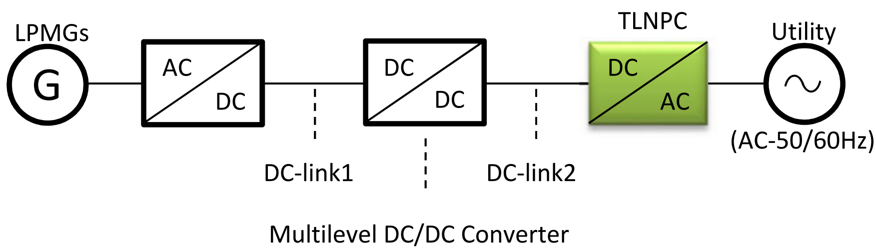


Figure 4.1 Three-level NPC inverter based the grid coupling system

4.1 TLNPC inverter

Considering the advantages in the power handling capability and the easiness in control, the TLNPC converter is a desirable solution for many industrial applications. The commercial availability of its phase-leg units as modules reduce the effort for converter assembly. Even now, many semiconductor suppliers are focusing on the improvement of the packaging and the power handling capability of such modules [24].

As shown in Figure 4.2, each phase leg of a TLNPC has four switches and two clamping diodes. These diodes are connected to the capacitor neutral point for voltage clamping. Two of the four switches are always ON to provide three levels in the phase voltage waveform.When two upper switches are ON, the phase voltage is half of the DC-link voltage. When two middle switches are ON, the phase voltage is zero. The phase voltage is negative and equal to half of DC-link voltage when two lower switches are turned ON.

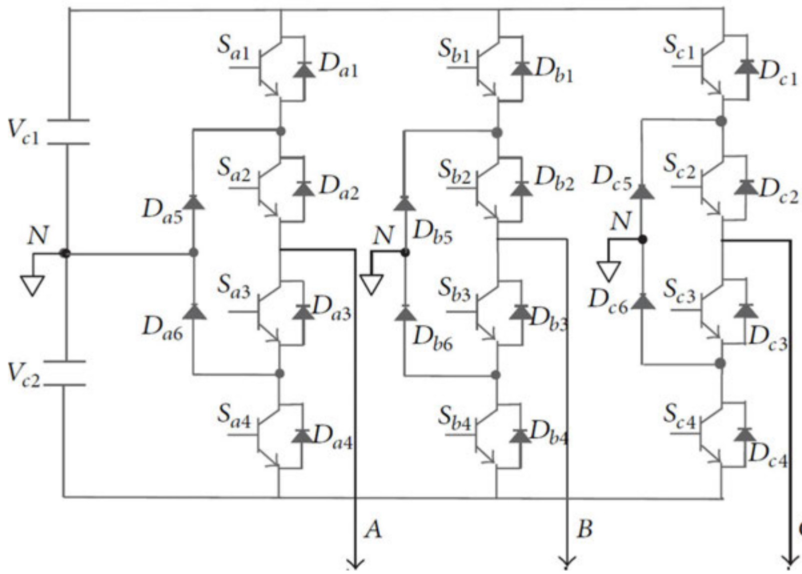


Figure 4.2 Three-level three-phase NPC inverter

4.2 Modulation techniques

The main modulation techniques for the TLNPC inverter are the carrier pulse width modulation (CPWM) and the space vector PWM (SVPWM) [25].There exist, three distinct PWM strategies for CPWM

- Alternative phase opposition disposition (APOD), where the alternate carrier waveforms are phase shifted by 180◦.
- Phase opposition disposition (POD), where the carriers above the reference zero point are out of phase with those below zero by 180◦.
- Phase disposition (PD), where all carriers are in-phase across all bands.

For the TLNPC converter, good harmonic performance is significant. Modulation and control techniques can improve the output power quality. Several studies have been carried out to choose the optimum method in terms of performance and digital implementation as mentioned in Paper VII. Another contributor for the harmonics at the converter output is the dead-time implementation. More details regarding dead-time in an NPC converter is given in the following Section and also in Paper VI.

4.3 Dead-time analysis

Dead-time is the delay required in between the turn on and turn off gate pulses, applied to the complimentary switches in a phase leg of any inverter. Without using the dead-time delay, there is high chance for the DC-link short circuit, since both upper and lower leg switches might momentarily keep their ON state simultaneously during each complementary switching state transitions. In multilevel converters, dead-time implementation always need an extra effort due to the large number of devices. The authors conducted a study how the dead-time implementation alter the unit cell representation of a TLNPC converter PWM and how to draw the harmonic calculation results from that. This Section is based on the Paper VI.

The unit-cell representation of the several converters with different PWM techniques are well described by Holmes and Lipo in [25].

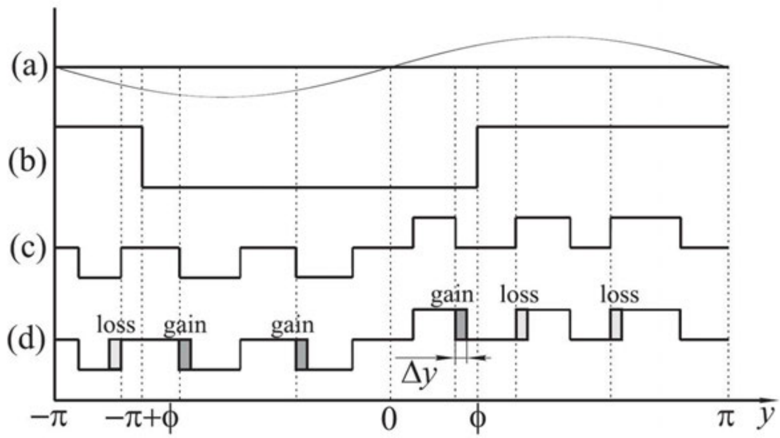
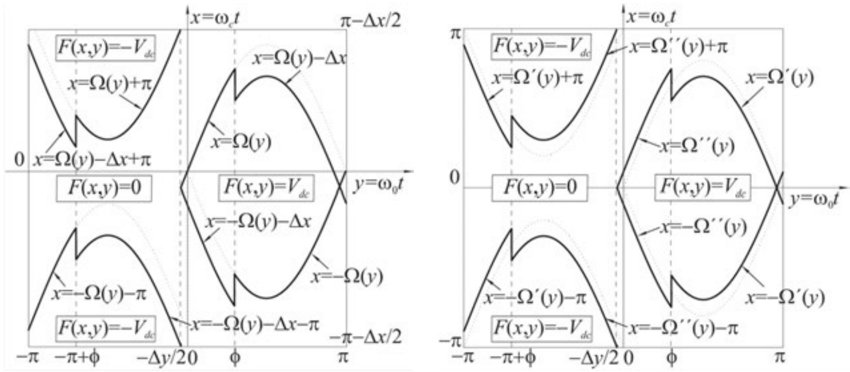


Figure 4.3 Dead-time effects for the FDTD case; (a) Modulation signal v_{id}; (b) Polarity of the current i_a; (c) Ideal output voltage; (d) Output voltage with the dead-time effects

There are two ways to introduce the dead-time for switching instants. In the 1st method, a delay is introduced for the 'ON' signal of switch, to allow the other switch to completely turn off. In this case, the applied time delay is equal to the dead-time, i.e., T_d. In the 2nd method, the dead-time can be introduced by advancing all turn-off times $T_d/2$ and delaying all turn-on times by the same amount. The reference terms used here for the 1st method is FDTD and for the 2nd method is HDTD.

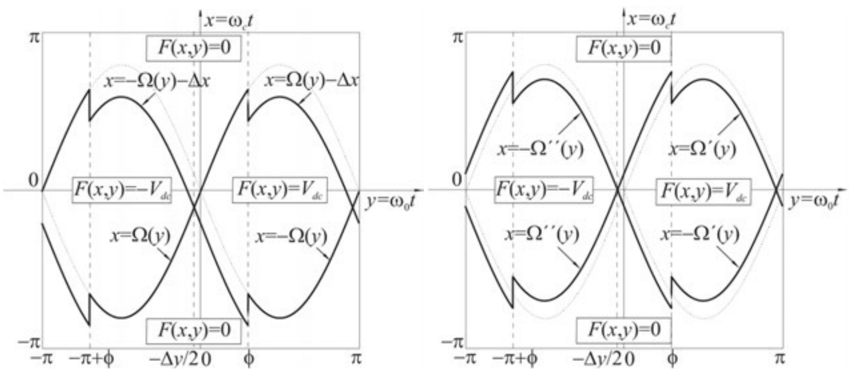
Let us consider the FDTD mode as shown in Figure 4.3. When y is in the region of $-\pi + \varphi$ to φ and the output current is negative ($i_a < 0$), a gain in the output voltage is obtained at the pulse falling edges. On the other hand, when y is in the region of φ to $\pi + \varphi$ and $i_a > 0$, a loss of voltage occurs at the pulse rising edges. In the case of three-level inverters, APOD coincides with POD. The unit-cell representation of three-level inverter in PD PWM and POD

PWM are presented in Figure 4.4 and Figure 4.5 and more details can be found in Paper VI.



(a) (b)

Figure 4.4 Unit cell of the three-level PD PWM; (a) FDTD case; (b) HDTD case



(a) (b)

Figure 4.5 Unit cell of the three-level POD PWM; (a) FDTD case; (b) HDTD case

4.4 Grid connection

The final goal of any renewable energy conversion system is to feed the produced electric power into the utility network, so that the power can be transferred to the desired locations. The main requirement for interconnecting such a renewable source to the power network is to satisfy the grid codes. More details about the grid codes are listed in [26]. The two main tasks of a grid tied power converter are synchronization and power flow control. Synchronization of the generated voltage with the voltage at point of common coupling (PCC) is achieved by using phase locked loops (PLLs). To control the power flow, the DC-link voltage and inverter currents are controlled. More details can be found in Paper VII.

Another grid synchronization method using Kalman filter, is presented in Paper XII. Stationary reference frame based Kalman filter (SRF-KF) for grid synchronization is considered. Regular methods in literature uses ABC reference frame which needs three Kalman filter blocks. The stationary reference frame method decreases the computational complexity by reducing the Kalman filter requirement to two. This work is in preliminary stage and needs more research to find the feasibility of this method in system level.

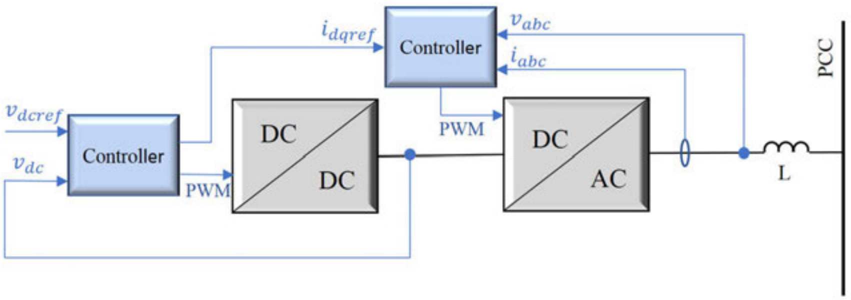


Figure 4.6 Grid connected converter control scheme

4.5 Converter control

In the following Section, the control strategy used for grid-tied converter is explained. Voltage and current control scheme based on PI controllers, are represented in Figure 4.6.

4.5.1 Voltage control

The DC-link voltage can be controlled either by DC/DC converter or by the inverter itself. The first method is chosen here for the digital implementation. The DC-link voltage control by DC/DC converter is well illustrated in Chapter 3. In addition, the DC-link voltage control calculates the reference current for the inverter current control.

4.5.2 Current control

In most of the applications, the performance of the voltage source inverter (VSI) depends on the quality of the applied current control strategy. It enhances the accuracy of the instantaneous current waveform and provides the peak current protection, overload rejection and compensation for the load variation. The well-known synchronous reference frame (SRF) current control method is used for the implementation and testing of the grid-tied converter system here. The block schematic for the SRF control is shown in Figure 4.7.

The SRF current regulator uses the dq reference frame to convert the signals from stationary frame to synchronously rotating frame and to perform the frequency shift on the system signals. The first step is to transform the signal in abc frame to $\alpha\beta$ coordinates using Clark's transformation method. The zero-sequence current can be excluded in a three-phase balanced system. To achieve zero steady state error, the stationary reference frame signals are converted to dq frame using Park's transformation matrix.

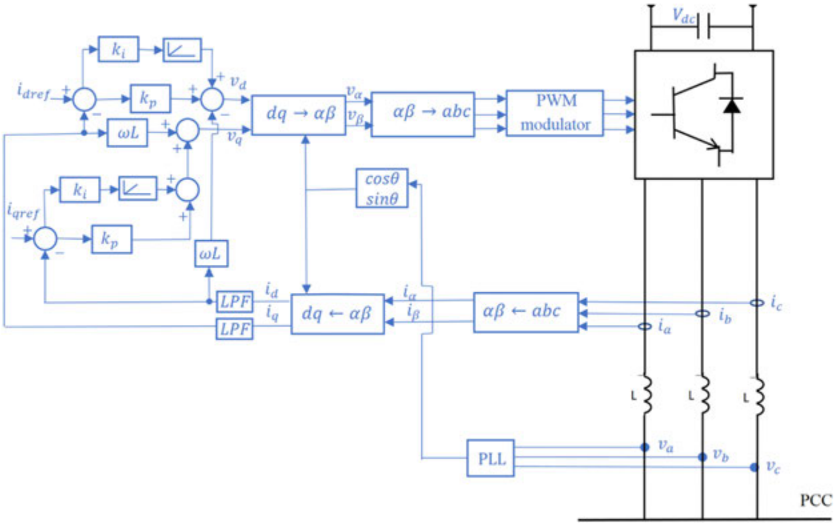


Figure 4.7 Synchronous reference frame based PI current controller

4.6 Prototype of TLNPC inverter

A hardware prototype of TLNPC inverter is constructed in the laboratory to test the grid coupling of the WECs with suitable control strategies. The initial, testing of the NPC inverter is done as a stand-alone unit without coupling to WECs and TLBC. The hardware prototype is shown in Figure 4.8.

The inverter hardware main building blocks are the special IGBT packages SKM 300MLI066TAT from Semikron which consists of a TLNPC inverter leg as shown in Figure 4.9. These legs are robust, convenient and cost-effective solutions for the NPC inverter hardware and three of these are used for the 3 legs of the three-phase NPC inverter hardware prototype.

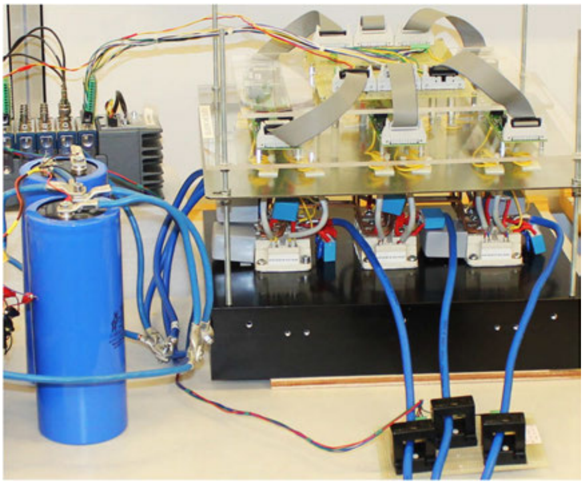


Figure 4.8 Three-level NPC inverter hardware prototype

The inverter modulation and closed loop control algorithms are implemented in the same CompactRIO hardware used for the TLBC control. Six dual channel gate drivers Concept 2SC0108T2A0-17 mounted on the evaluation board 2BB0108T2A0-17, are used to drive the 12 IGBT switches of the TLNPC inverter.

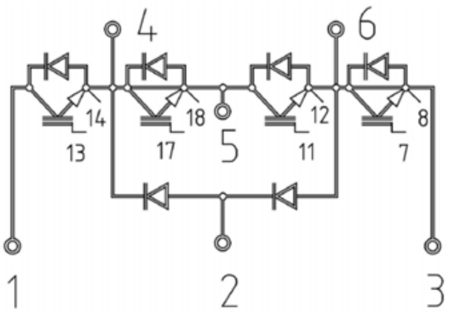


Figure 4.9 Internal layout of SKM 300MLI066TAT - TLNPC inverter LEG consisting of 4 IGBTs, 4 inverse diodes and 2 free-wheeling diodes

5 Interconnection strategies

In this Chapter, the key interconnection strategies and their significance in the WECs to grid interconnection system is described. The crucial interconnection point is the common coupling point (DC-link1) of the WEC-rectifier units, as highlighted in Figure 5.1. The Chapter also outlines the WEC-rectifier unit properties and the reasons for using diode rectifiers. The Chapter is based on Papers VIII and IX, where more details can be found.

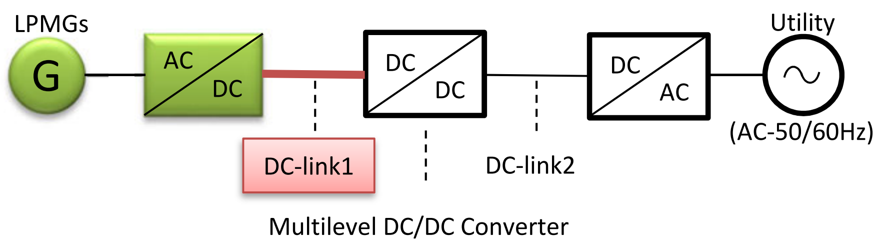


Figure 5.1 The key interconnection point - DC-link1, of the WEC – Rectifier units is highlighted in the WECs to grid multistage converter system

5.1 Need for interconnection strategies

The previous Chapters listed the most important developments in the TLBC power converter and TLNPC inverter to provide better adapted and intelligent power conversion stages for the WECs - grid interface. Considering the large voltage variations in WEC output, almost from zero to few hundreds of volts, even no improved power converters have enough bandwidth to handle such input variations. In this regard, adapting a suitable interconnection strategy, especially at the point of interconnection of WEC-rectifier units can complement the power converter efforts to stabilize the DC-link. In other words, intelligent interconnection strategies can improve the steadiness of accumulated power output from multiple number of WECs which in turn will provide satisfactory input conditions for the power converters to perform its normal operation all the time, except in extreme power conditions. This results in a large improvement of system utilization and cost effectiveness of the entire power conversion system. It can also effectively eliminate the switch gear and large filter requirements after the rectification stage and can reduce the component costs.

5.2 WEC-rectifier units

The WECs as described in chaper1, are of type Direct-driven point absorber type Linear permanent magnet system (DDLPMG WECs). Most of them are three-phase generators with output reflecting random nature of input waves as shown in Figure 2.1. Thus, the electrical output parameters like voltage, current, frequency and phase change continuously. Each generator has a dedicated 3 phase diode bridge rectifier so that the random AC signal is converted to corresponding DC signal before it is coupled to similar outputs from other generators.

5.2.1 Selection of passive rectification

Even though the active rectification has many advantages over the passive rectification method, the current work utilizes passive rectification method. In simple terms, the main reasons are cost, complexity and reliability. Need for active rectifier for each generator can increase the converter and sensor cost and control complexity a lot. Moreover, active rectification control requires several measured electrical parameters from the generator. Adding translator position, voltage, phase and other sensors inside the underwater LPMG is complex, difficult and costly, may also affect the reliability of the system. Instead, having a passive rectifier stage followed by suitably controlled DC/DC converter and an inverter can improve the overall performance of the system which can be comparable to active rectifier based system. Having a suitable interconnection strategy at the diode output stage is also vital and can eliminate shortcomings due to passive rectification to a larger extend. Even though passive rectification is utilized in the current work, it is important to do future research on active rectification strategies for the WECs, especially with sensor less controls in order to compare and decide its merits and demerits with the current passive rectification method.

5.3 Interconnection methods

The farm level spatial distribution of WECs and interconnection is one of the main aspects when talking about the wave farm concept. Since the thesis work only concentrate on the electrical side of the WEC system, it mainly talks about the electrical interconnection of WECs in various methods irrespective of the farm distribution. The DC-link1, which is the point of interconnection of multiple rectifier outputs from various WECs, is analyzed mainly in order to find the optimal interconnection strategies for the future system. Mainly the DC-link stress due to power fluctuations, maximum and minimum voltage levels, filter and DC storage requirements and the overall system stability are *G*taken into consideration for finding the suitable interconnection strategies.

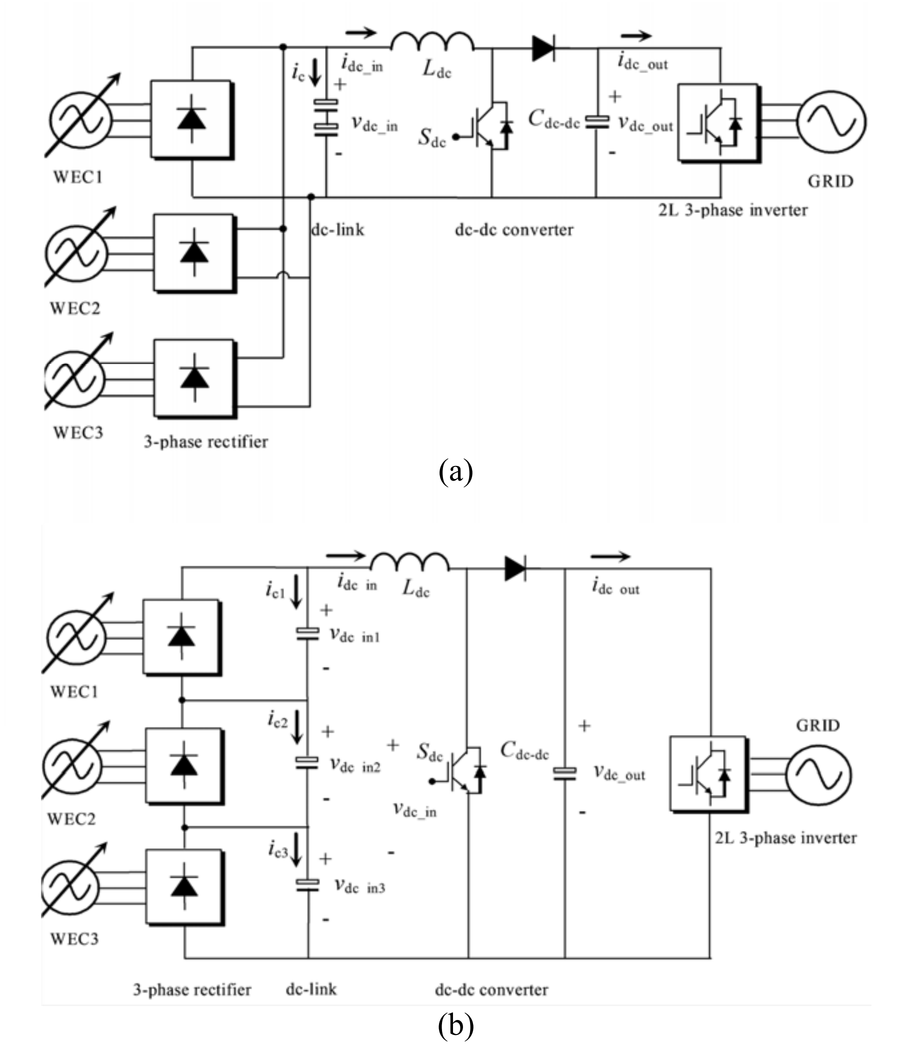


Figure 5.2 WEC-rectifier units' interconnection methods to form DC-link; (a) Parallel interconnection; (b) Cascaded type interconnection

For comparison, the work starts with simply analyzing the stress due to single generator operation and then using multiple generator interconnection to form the DC-link1as shown in Paper VIII. In Paper IX mainly parallel and cascaded interconnection possibilities are analyzed as shown in Figure 5.2.

The interconnection possibilities using series and cascaded topologies exhibit unique capabilities in each case. These are still preliminary results from the research found in these papers and there is a need for more extensive testing to see what can be the optimal option. Especially hybrid topologies combining both parallel and cascaded methods like phase cascade bridge rectifier array configurations seems to be the future areas to research for finding the optimal solution for interconnection of DDWECs.

6 Hardware development

This Chapter outlines some of the important hardware development carried out during the project. All the converters used in this work are developed in the laboratory and customized for various tests and applications. This includes 3 phase diode rectifiers, TLBC and TLBBC three-level DC/DC converters, TL NPC inverters, IGBT gate drivers, measurement systems, Embedded controls in FPGAs and also in NI Labview CompactRIO etc. In this Chapter, mainly the multilevel multistage converter system used for the WECs to grid integration - testing is summarized.

6.1 Laboratory setup

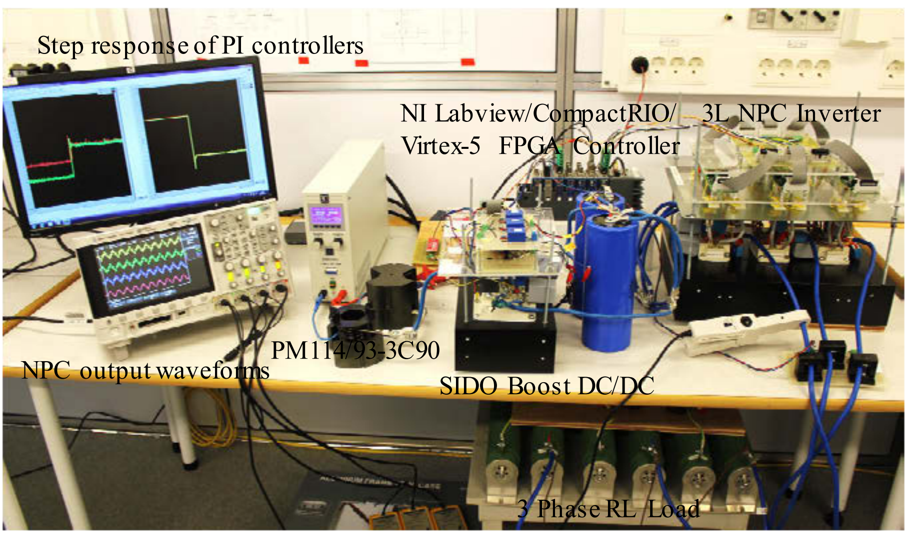


Figure 6.1 Laboratory hardware setup for developing and testing converter controls

The first stage in the hardware development work mainly focuses on the development of laboratory prototypes for testing the converter system using various modulation schemes and control strategies. Laboratory hardware prototype mainly includes a TLBC converter and TLNPC inverter designed for the WEC to grid integration. Details and specifications of the TLBC and NPC inverter prototypes are already described in 3.2.5 and 4.6 respectively. NI CompactRIO with Virtex-5 FPGA is used to implement the entire closed loop control for both DC/DC and DC/AC converters. Control logic is coded in Labview. Direct FPGA implementations of the entire control using VHDL on a custom PCB is preferred for the real hardware due to the cost and size advantages.

Figure 6.1 shows the laboratory setup for testing of modulation and control strategies. IGBTs from Semikron, gate drivers from Concept, capacitors from FTCAP, inductor cores from Ferroxcube, compact DC and AC power supplies from Traco Power, voltage and current sensors from LEM, CompactRIO and add on modules (ADC, DAC, Digital I/O etc.) from National Instruments etc. are some of the main components used for construction of the converter hardware.

6.1.1 IGBT gate driver circuits

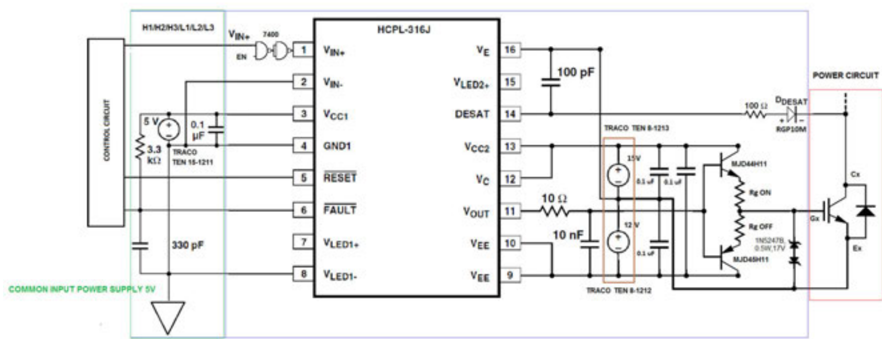


Figure 6.2 Custom IGBT gate driver circuit developed in the laboratory

The work started with developing and/or selecting a suitable IGBT gate driver circuit for the converters with all the protective features and reliability. A custom IGBT gate driver circuit is developed in the laboratory in order to study its operations, performance and reliability for the application. More details of the custom IGBT gate driver circuit can be found in Paper XI. A rough schematic of the first gate driver developed in the laboratory is shown in Figure 6.2. Later, comparing this gate driver with various industrial gate drivers, based on the cost, development time, reliability etc., it is decided to continue with the 'Concept' gate drivers for the application. They are of comparable cost and readily available in the market. Figure 6.3 shows the basic Concept driver assembly in 12-pulse configuration for driving TLNPC inverter gates. Concept 2SC0108T2A0-17 driver is mounted on the evaluation board 2BB0108T2A0-17 for making a full driver setup. Six of these dual channel driver configurations are used for the 12-pulse configuration.

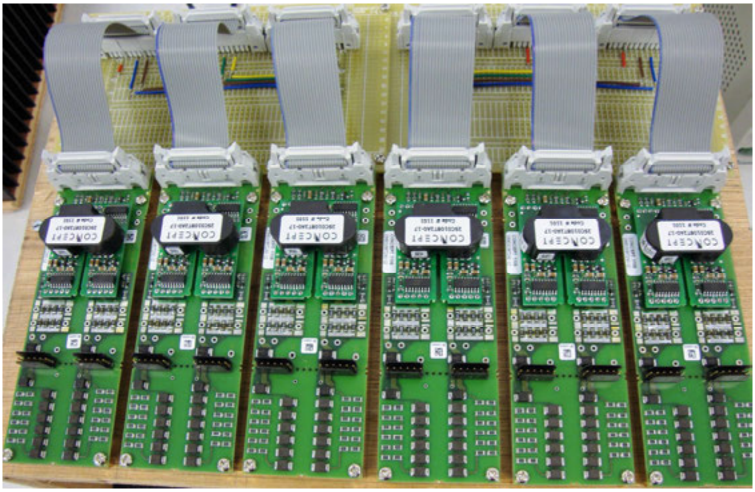


Figure 6.3 Concept driver assembly 12-pulse configuration for driving TLNPC IGBT-gates

Concept drivers provide high frequency transformer based galvanic isolation for both gate control signals and for fault feedback signals. There are other sensor feedback signals and control signals which also need galvanic isolation. Isolation mainly helps to protect the low voltage digital control hardware from the high voltage power hardware side. This also helps to reduce signal interference and Electromagnetic compatibility (EMC) issues. Thus, later an interface circuit is developed in order to provide optical isolation for all the signals flowing between embedded controller and power converter system as shown in Figure 6.4.

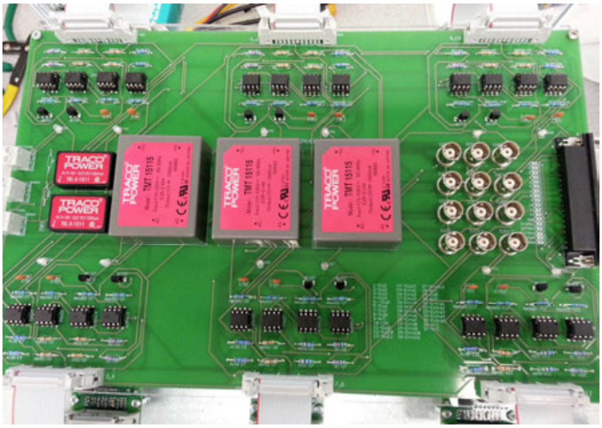


Figure 6.4 The converter signal interface circuit with opto-couplers, amplifiers, DC power supplies and various types of interface connectors.

The circuit also amplifies the control and feedback signals between converter and controller so that error due to weak signals can be eliminated.

6.1.2 Control hardware

The control hardware is one of the most important part of the converter system and NI CompactRIO is selected as the control hardware since the system is very much flexible and support quick development during research phase. cRIO-9022 CompactRIO embedded real time controller with advanced control and monitoring capabilities is combined with an 8-Slot, Virtex-5 LX50 FPGA CompactRIO Chassis - cRIO-9114 for adding C Series I/O modules to support the distributed control or monitoring application.

Figure 6.5 A typical hardware setup example of the CompactRIO system using cRIO-9022 and cRIO-9114

Figure 6.5 shows a typical setup of CompactRIO system with FPGA chassis and add-on modules. The add-on modules are selected based on the control and monitoring requirements for the TLBC converter as well as NPC inverter. Digital I/O module, ultra-fast digital I/O module, analog to digital (ADC) module, digital to analog DAC module etc. are some of the main modules used in the project. I/O modules are directly configured and assigned to FPGA pins which allows concurrent signal processing of the I/O signals while the real-time processing stage of the CompactRIO handles the high-level control and interfacing functions. It also has fast ethernet connectivity which provides direct LabVIEW - GUI based computer interface to program, control and monitor the entire controller operation.

6.1.3 Measurement system

The measurement system including control feedback signals as well as monitoring signals are mainly made up with various current and voltage sensors from LEM and interface circuits. Suitable ADC modules are used in the NI CompactRIO FPGA interface to acquire these measured signals. Current transducers LA 55-P, HAL 50-S and voltage transducer LV 25-P are some of the commonly used sensors in this hardware. Since these sensors have built-in galvanic isolation, the signal outputs are directly fed into the input of the ADC module of the CompactRIO.

6.2 Hardware setup for the onshore testing

After the successful laboratory testing of the hardware developed, the prototype has been used for the real field testing of the WEC to grid multistage converter system, in order to understand its real-world suitability. The converter system including three-phase diode rectifier, TLBC converter and TLNPC inverter are organized/stacked inside a vertical cabinet as shown in Figure 6.6. All the sensors and measurement boards, various breakers, storage capacitors and the entire control system with CompactRIO with add-on modules are fitted into the same cabinet to make the system complete.

Figure 6.6 Field test arrangement of the WEC to grid interconnection multistage multilevel converter system.

6.3 AC2AC direct converter hardware

There is also an advanced hardware development work during the latter part of the project which will be described in Chapter 7. Multistage converter system including rectifiers, DC/DC converters and inverters are mainly used as the AC/AC converter system required for the grid connection of WECs. AC2AC direct converter hardware development is an entirely different and latest approach where a single stage direct converter does the AC/AC conversion task, which could be the future of these kind of conversion systems.

7 AC2AC direct converter MMC

The Chapter is based on the research work conducted during the EIT KIC InnoEnergy doctoral research mobility to Siemens AG, Corporate Technology, Power Electronics Group at Erlangen in Germany. During this time, the research focus was to develop a more advanced converter for AC to AC direct conversion applications using the MMC (Modular Multilevel Converter) technology. The AC2AC direct converter technology described here is patented by Siemens and more details can be found in [27].

The AC2AC direct power converter system can be seen as the future of such technologies including the current research work listed in previous Chapters, where multilevel multistage converter system can be replaced with a multilevel single stage converter system for applications like VRE grid integration, smart grids, traction etc.

7.1 Objective and motivation

Most of the industrial solutions for AC2AC conversion, including the wave to grid integration system described in this thesis employs multistage converter systems. For example, wave to grid coupling system described in pervious Chapters has three stage power converter system consisting of rectifier, DC/DC converter and Inverter. It also needs large storage at the DC-link to stabilize the system. A lot of other areas like power systems, smart grids, traction systems etc. also need AC2AC converters which are presently multistage systems. The current research project in Siemens tries to develop a single stage direct converter system to convert from three-phase AC to single-phase AC. This is attractive for the future since it can replace many industrial multi stage conversion systems to reduce cost and size.

7.2 AC2AC direct converter topology

AC2AC direct converter is based on the Modular multilevel converter (MMC) structure. The basic circuit diagram for the AC2AC direct converter is shown in Figure 7.1. Each MMC cell/module is a full bridge single-phase converter. A total of 72 modules are used for the structure which makes 12 modules per arm of the MMC. Each phase of the three-phase input voltage can be applied through the center of each arm while the single-phase output can be obtained between the two ends of the arms as shown in Figure 7.1.

7.2.1 Operating principle and features

A smart control strategy is used for controlling each cell of the MMC. Using intelligent sorting and sequencing algorithms to control the switching of each cell, the three-phase voltage input at the MMC can be derived into the single-phase voltage output. The control ensures that the voltages across each module capacitors are at its desired level and also maintain the total voltage across each arm constant.

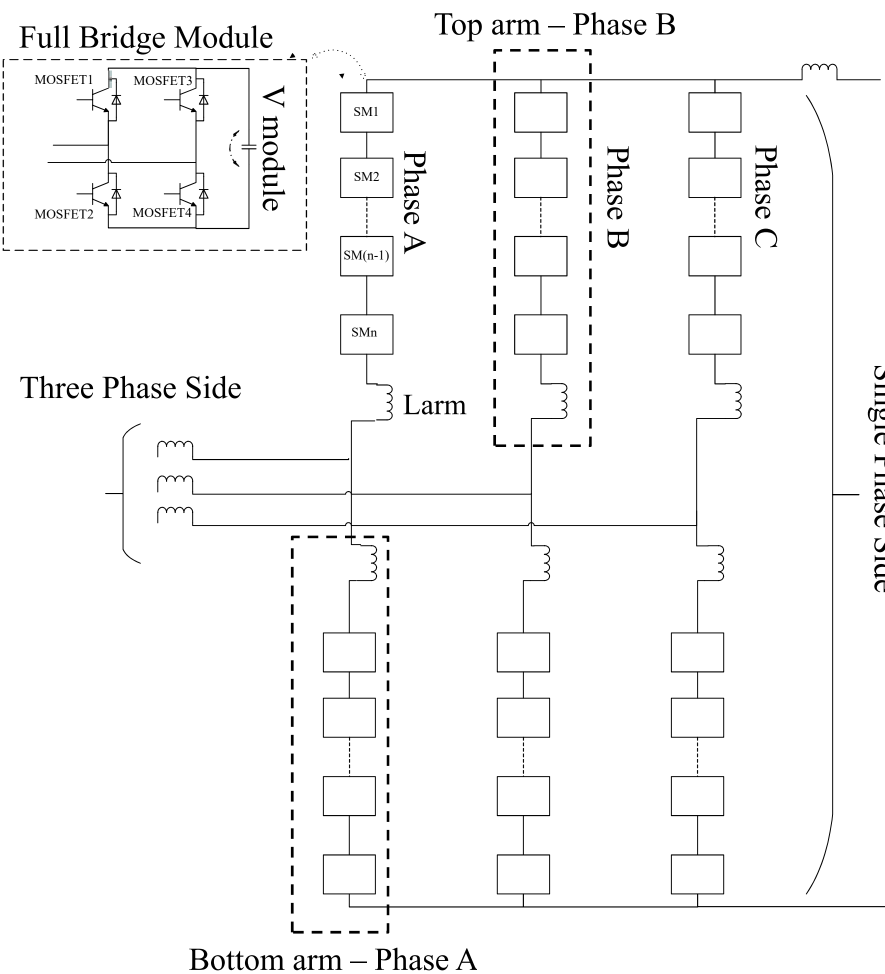


Figure 7.1 AC2AC Direct Converter MMC structure

The topology can directly convert three-phase AC voltage of any frequency and amplitude to the single-phase AC voltage of a different frequency and amplitude. It supports wide frequency of operation. It is mainly useful for medium to high voltage applications.

7.3 Hardware development

One of the most challenging work associated to the AC2AC converter is its hardware development. It has two main areas, one is the power hardware development and the other area is the control hardware and software development. The power hardware developed during the project is shown in Figure 7.2.

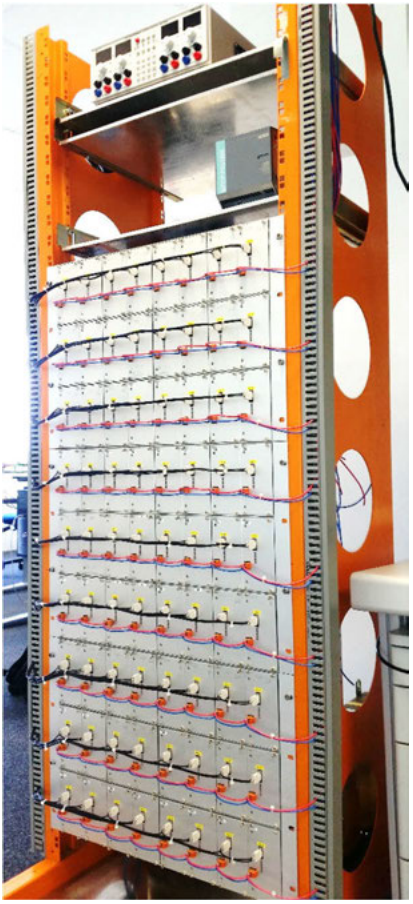


Figure 7.2 AC2AC Direct converter power hardware development

7.3.1 Embedded FPGA based real-time distributed control and communication hardware

During the second part of this project, the focus was given to the development of control and communication hardware for the AC2AC direct converter. The system is based on 72 Altera Cyclone FPGAs present in the 72 MMC modules and 1 master controller FPGA based on Altera Stratix technology. An optic fiber based communication network is established to control and coordinate FPGAs' functions. Serial communication strategies are also designed in order to maintain the real-time control of this distributed system using the master slave architecture. A test setup during the development consisting of one master and two slaves is shown in Figure 7.3.

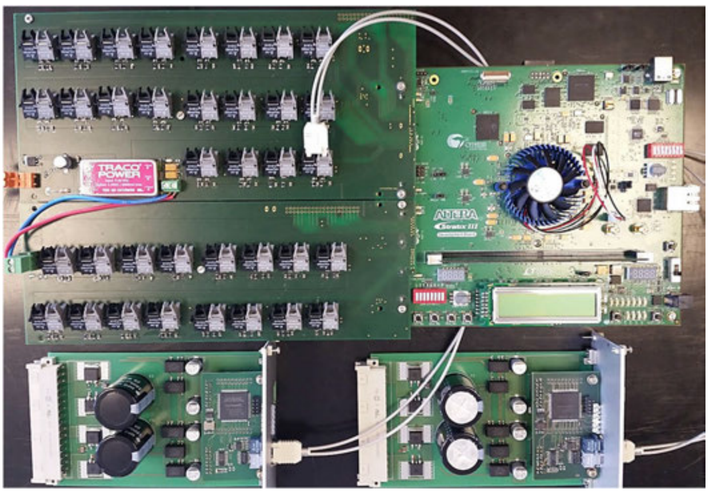


Figure 7.3 Real-time distributed control platform based on optic fiber networked FPGAs

Control and communication algorithms are coded using VHDL and directly downloaded to the FPGAs. Local protection and other features are maintained in the slave FPGAs of each module while the system level control and communication logic is coded into the master FPGA so that it can control and coordinate all the slave modules according to the central control logic.

7.4 Conclusions

The AC2AC direct converter can become a very attractive solution for many industrial applications. In order to keep the industrial confidentiality, only limited details are presented here.

8 Results and discussion

This Chapter comprises some of the important analytical, simulation and experimental results from various investigations performed on converter or system level. The important results are presented based on the Chapter order.

8.1 Load voltage regulation for TLBC

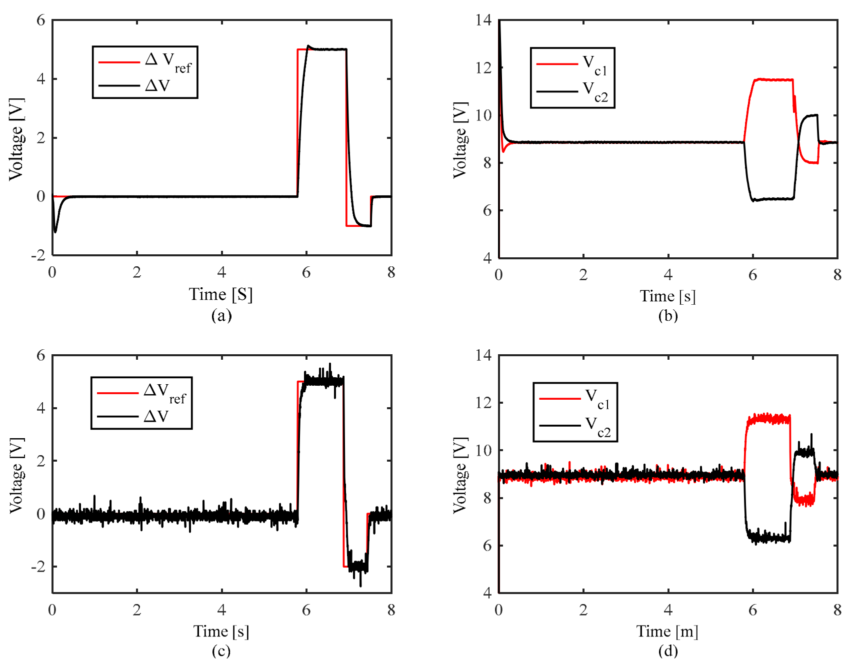


Figure 8.1 Simulated waveforms of TLB converter: (a) Step response of pulse delay controller; (b) Capacitor voltages. Experimental waveforms: (c) Step response of pulse delay controller; (d) Capacitor voltages.

The studies on the multilevel DC/DC converters have started with analyzing the TLBC. At first, the modes of operations and the load voltage regulation capability by PDC is investigated in simulation. To validate the simulated performance, the TLBC hardware is built and tested. The performance under simulation and testing are provided here. In Figure 8.1, the step response of the pulse delay controller (proportional integral type) is showed in terms of capacitor voltages, in both simulation and experiment. The required capacitor voltage difference ΔV_{ref} is given as the reference input to the pulse delay controller and the actual voltage difference ΔV follows the same path as shown in Figure 8.1 (a) and (c). The capacitor voltages V_{c1} and V_{c2} shows the corresponding change in upper and lower capacitor voltage, in order to satisfy the voltage difference demanded by the controller as shown in Figure 8.1 (b) and (d).

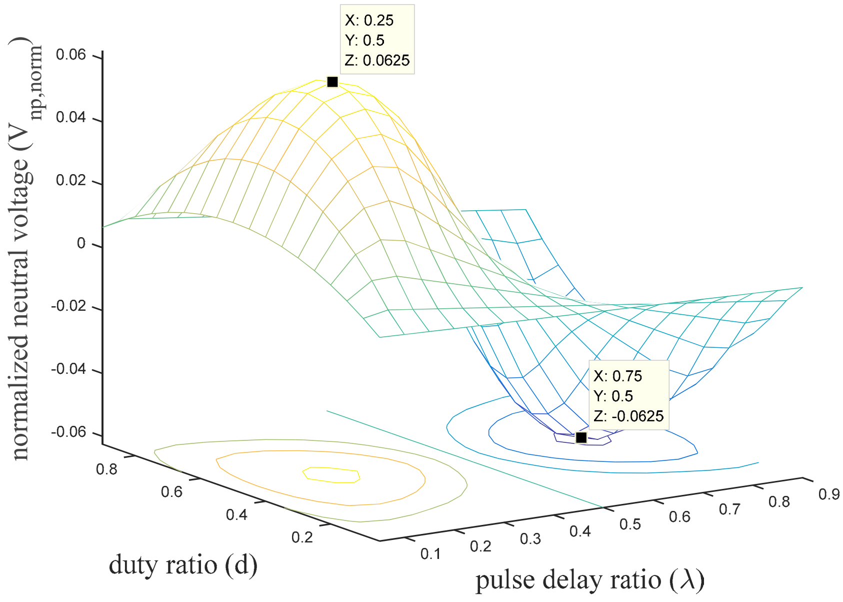


Figure 8.2 Normalized cross-regulation voltage for three-level boost converter

Figure 8.2 represents the maximum cross regulation voltage calculated for TLBC. The maximum normalized cross-regulation voltage is ±0.0625. More details can be found in papers II and III.

8.2 Cross regulation of TLBBC

The load voltage regulation studies have been extended to TLBBC to compare its cross-regulation capability against the TLBC converter. As per the analysis, the TLBBC has higher cross regulation capability over TLBC and the maximum normalized cross regulation voltage is ±0. 1467. Figure 8.2 and Figure 8.3 indicate theoretical maximum normalized value for each duty ratio and pulse delay ratio for TLBC and TLBBC respectively. However, in practical scenarios, these values can be lower than that calculated here due to peracetic drops, the component lead impedances and losses in the switches and diodes. This can restrict the converter from achieving these peak values.

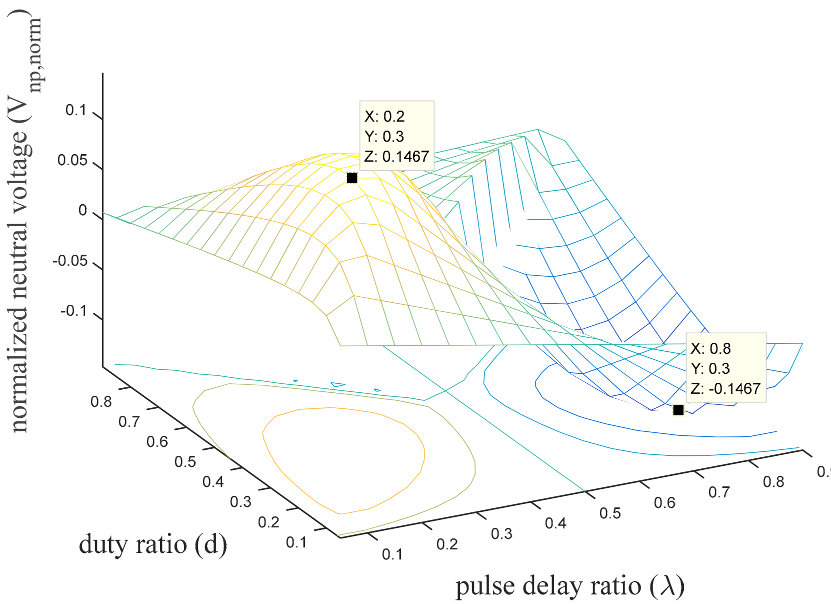


Figure 8.3 Normalized cross-regulation voltage for three-level buck-boost converter

The detailed analysis and experimental results for TLBBC can be found in Paper IV.

8.3 Capacitor voltage balancing of NPC using TLBC

The DC voltage control and the capacitor voltage balancing are achieved by PI controller based duty ratio and pulse delay regulation. The PI controller parameters are designed by inductor current ripple averaging method. The main advantage of conventional three-level operation of TLBC is the lower inductor ripple amplitude compared with conventional boost converter. But, the imbalance compensation voltage in each mode depends on the inductor stored energy in the preceding mode. The full range variation of delay gives higher compensation voltage than in the three-level conventional operation, but increased ripple current.

Compared with the conventional three-level switching used in SSPDC, 18.43% higher compensation voltage can be achieved by PDC method.

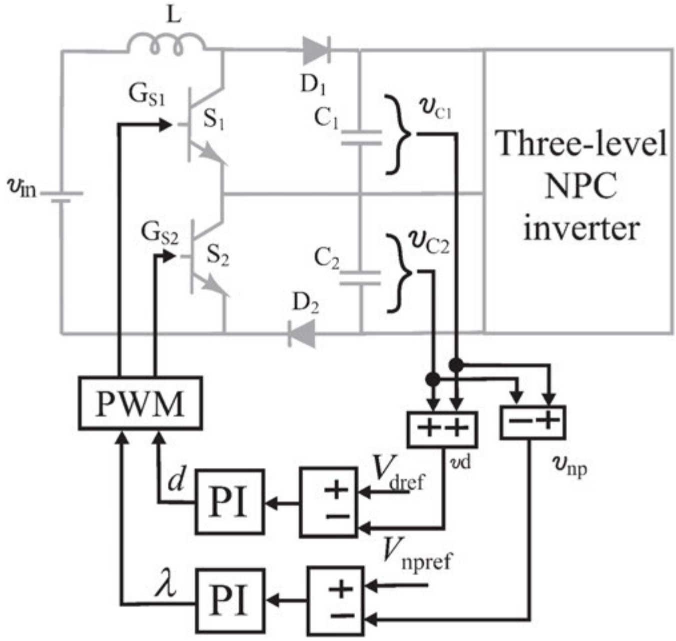


Figure 8.4 Capacitor voltage balancing control along with boost control performed by TLBC

Figure 8.4 shows the block schematic of control method for TLBC. The PDC controller senses the voltage difference between the two DC-link capacitors and compensate for the imbalance. Most of the cases, the reference for the neutral point voltage is set to zero so that the controller regulates each capacitor voltage to be the same. At the same time, boost controller senses the total DC-link voltage and adjust the duty ratio accordingly to obtain the desired voltage boost and regulation at the DC-link. Thus, combined action of both controllers results in the desired DC-link power conditioning.

The controller step response for voltage regulation and balancing operation is demonstrated in Figure 8.5. Both total DC-link voltage and individual capacitor voltages are regulated simultaneously by the two controllers. The NPC inverter output response to each control action can be also seen in the figure. It can be seen that the performance of the controller is satisfactory for achieving the desired cross-regulation.

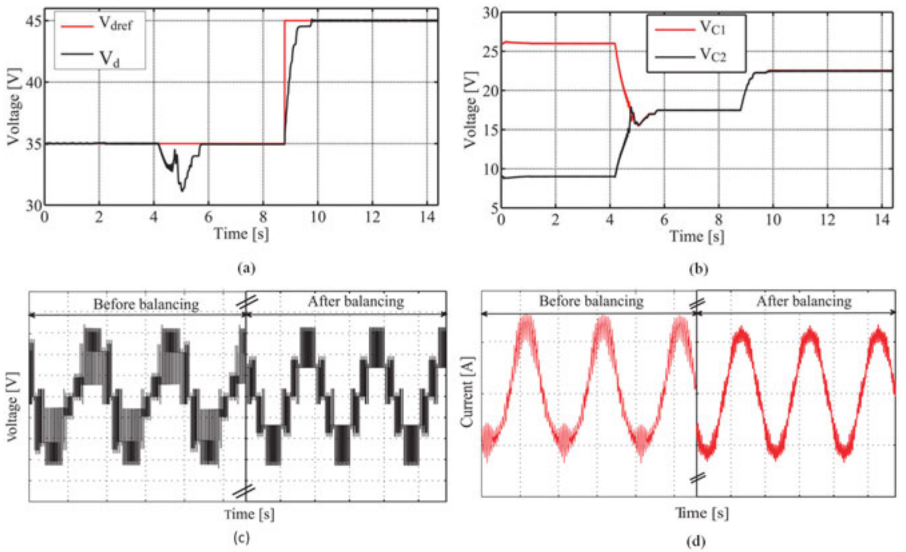


Figure 8.5 Step responses of total DC voltage and capacitor balance voltage (a) PI controller response for DC voltage control (b) Lower and upper capacitor voltages before and after voltage balancing (c) NPC inverter output voltage waveforms before and after capacitor voltage balancing (d) NPC inverter output current waveforms before and after capacitor voltage balancing

8.4 Cross-regulation using TLBBC

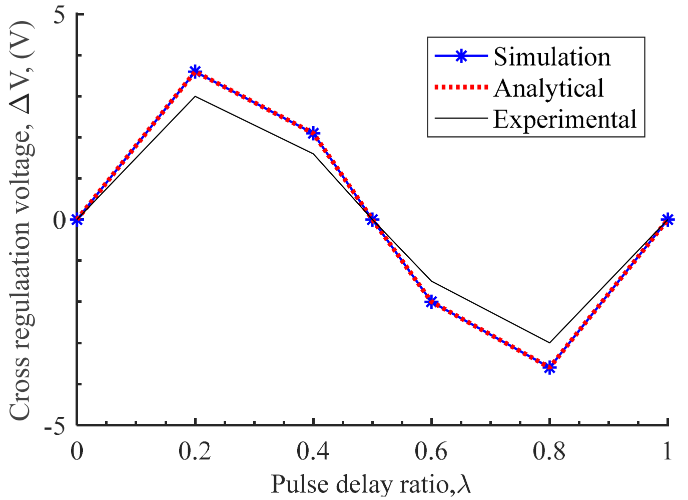


Figure 8.6 Comparison of ΔV obtained by the PDC of TLBBC from analytical, simulation and experimental results

The cross-regulation or capacitor voltage balancing capabilities of TLBBC is investigated analytically, in simulation and experimentally. The results are shown in Figure 8.6.Eexperimental results shows a lesser amplitude due to the various losses present in the hardware.

8.5 Control of NPC for grid connection

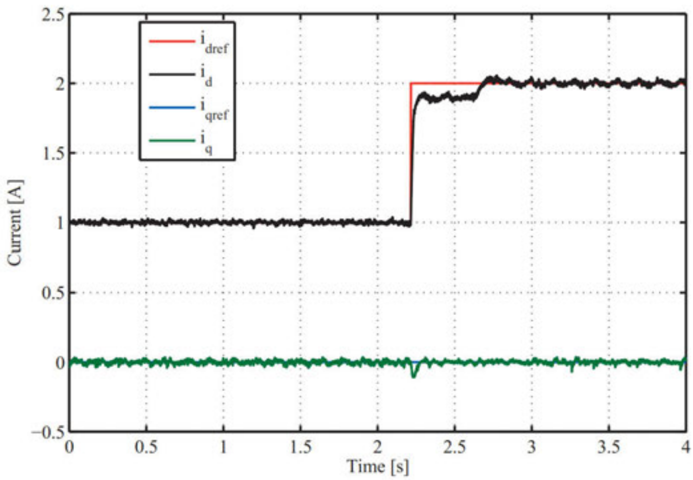


Figure 8.7 PI current controller step response for the active and reactive power demand. Normally reactive current demand part i_{qref} is set to 0.

The synchronous current control is applied to the NPC inverter in order to enable the grid coupling. Figure 8.7 shows the step response of PI type current controller. To enable unity power factor operation, the quadrature component of the current reference is set to zero. The controller response to both i_d and i_q demands are satisfactory.

8.6 WEC-rectifier and TLBNPC onshore test

After the successful laboratory testing of the entire converter system, they were tested in Lysekil project site to study the real-world performance. Due to the cost and availability concerns an onshore testing with one LPMG is performed as a preliminary study. A crane is used to lift the translator of LPMG up and down to simulate the wave response of WEC as shown in Figure 8.8 (a). The converter system input was connected to the three-phase output of LPMG and the output was connected to an RL load. The converter system is shown in Figure 8.8 (b). LabVIEW based GUI is used to interact with the converter system and to observe the controller performance as shown in Figure 8.8 (c).

The converter system performed its normal operation when the translator was moving with higher speed. When the translator changes its direction at the end stops of LPMG, the power becomes near zero for a short time and thereby, the converters or the DC-link storage couldn't perform its normal operation. Thus, it became clear that, in order to have a feasible test platform, multiple WECs with suitable interconnection methods are essential.

Figure 8.8 Onshore testing of the converter system connected to LPMG output; (a) A crane is used to move the translator up and down to simulate the wave response from the WEC; (b) The power converter systems including rectifier and TLBNPC connected to RL load; (c) LabVIEW GUI showing the converter control response.

9 Conclusions

In this Chapter, some important conclusions from this research project are listed. The facts are listed below, more details can be found in the corresponding papers.

DDLPMG for wave energy conversion requires intelligent power converter solutions for grid connection, due to its highly varying output characteristics. Converters with special features like large controllability range, embedded intelligence, field programmability, scalability and high reliability are desired for such applications. Three-level boost and three-level buck-boost converters can be used for the better power conditioning of the DC-link for VRE grid integration applications. Using such already existing converter technologies with smart control, in order to improve and adapt them for this application, is a reasonable option in terms of cost and development time.

- The new pulse delay control and the conventional duty ratio control can be combined to obtain a smart controller for the TLBC and the TLBBC, to largely improve their performance for renewable energy conversion applications. Controller design of TLBC and TLBBC can be performed unfailingly using the Inductor current ripple averaging method. Entire 10 cases of operation of TLBC and TLBBC are useful for designing smart controllers with higher controllability range.
- Even though discontinuous conduction mode of TLBC has many advantages, the unknown zero current switching periods during its operation makes the controller design complex.
- Active capacitor voltage balancing of TLNPC inverter DC-link by using TLBC can make it an attractive solution for the renewable grid integration.
- The current controllers using PI compensators in synchronous reference frame with DC/DC converter based voltage control provide efficient grid side control for the grid connected TLNPC.
- Contour based dead-time harmonics modelling for the TLNPC, can help to improve the NPC output harmonic performance by designing suitable dead-time compensators.
- WEC-Rectifier units' interconnection strategies to form the DC-link have a major role in optimizing the power conversion system and also can reduce the DC-link stress. A suitable strategy can complement the power

converter efforts to stabilize the DC-link. More techniques like phase cascade bridge rectifier arrays looks attractive for the future improvements in this regard.
- FPGA based smart controllers with fast communication capabilities are an attractive future solution for many VRE and smart grid applications. They can bring out maximum performance of the power converters while making the entire system much more flexible and future proof.

The current research work unlocks several future possibilities for the VRE grid integration. WECs to grid integration using the TLBNPC converter with pulse delay control shows promising results for the future wave farm grid coupling. This shows that, already existing multilevel converter systems with FPGA based customized control can become cost effective and flexible converter solutions for the future smart-grid applications.

10 Future works

The current work can be seen as preliminary study on multilevel power electronic system for the VRE grid integration, control and communication area. There are several important findings during this study which opens the door for further research in the future. A number of important future works are listed in this Chapter.

10.1 WEC and wave-farm emulator and test platform

Offshore testing of power converter technologies for the DD LPMG based WECs are highly expensive due to the underwater works. Thereby, it is necessary to test the power converter system and controls thoroughly before their actual deployment. A solution came up during the current project is to develop a complete test bed at the lab with LPMG/ farm emulator and multistage power conversion and grid coupling system. A second TLNPC inverter with LPMG model is successfully tested to emulate the WEC characteristics. It indicates that wave data input to the emulator will produce LPMG three-phase output response and which can be utilized for the entire power conversion system testing. This work needs to be completed so that a complete emulation and testing platform can be developed in the laboratory to accelerate future research on grid integration of WEC units.

10.2 Interconnection strategies for WEC-rectifier units

As mentioned in previous Chapter, WEC-Rectifier units' interconnection strategies to form the DC-link has a major role in optimizing the power conversion system and in DC-link stress reduction. A suitable strategy can complement the power converter efforts to stabilize the DC-link. Series and cascaded interconnection techniques and hybrid techniques like phase cascade bridge rectifier arrays looks attractive for the future improvements in this regard. It is very important to find the optimal interconnection solution for the future, since it can meet the requirements and reduce the cost associated to the power converter systems.

10.3 Farm level testing of multilevel multistage converter system

The power converter solutions developed during the research project should be tested with a small wave farm to analyze and study its real-world performance. Further improvements and optimizations are very important based on these test results. Technology transfer to the wave industry for further testing and development can be another option for future.

10.4 Farm level simulations and optimizations

Another important area of future work is the full system simulation from Wave to Grid. MATLAB/Simulink based power converter system models are developed during the research project along with the hardware development. If the same models can be coupled with hydrodynamic models of the WECs/farm, then an entire wave to grid system can be simulated. Since this is an interdisciplinary area work, future collaboration with hydrodynamic project group is important.

10.5 Active rectification possibilities

The current work employs passive rectification and DC-link voltage control in order to achieve the power flow control from the WECs. It is also very interesting to try active rectification and control to estimate its performance compared to the current technique. It has many challenges to overcome as described in Chapter 2, but possibilities of sensor-less methods can be an attractive solution for the active rectification in this case.

10.6 DC-link storage optimization

DC-link storage is a very important and costly part of the multistage power conversion system. DC-link storage size can be reduced based on various factors like converter topologies, frequency of operation, interconnection strategies, smart control etc. Thus, storage optimization is also a very important future work which may help to reduce size and cost of the power converter system.

These are some of the important future works and scope associated to the current project, but in general, VRE grid integration using smart power electronics area needs a lot more research to find the optimal solutions which can contribute to the sustainable future.

11 Summary of papers

Paper I

Control and implementation of three-level boost converter for load voltage regulation

This paper investigates the control and the implementation of a TLBC for regulating the load voltages. A PI controller based PDC method is used for adjusting the load voltages at equal turn on and turn off time of the converter switches. The circuit simulation is done in Matlab/Simulink. The controller is realized by using the FPGA in LabVIEW/CompactRIO module. The simulation and experimental results show a validation of the controller for regulating the voltages. This method can easily be applied for voltage balancing in a three-level neutral point clamped inverter where neutral voltage imbalance is always an issue.

The author has contributed to the development of simulation model and has a major contribution in hardware set up. He has also participated in article writing.

Paper II

Pulse delay control for capacitor voltage balancing in a three-level boost neutral point clamped inverter

In this paper, entire operating modes of single input dual output (SIDO) boost converter is presented along with the new control method for capacitor voltage balancing of a three-level boost neutral point clamped (TLBNPC) converter. All the possible cases which contribute to the voltage balancing, are employed for capacitor voltage balancing. PI controller based duty ratio control and PDC are used for DC-link voltage regulation and capacitor voltage balancing. In PDC, the delay between two pulses varies from zero to T_{SW}. Since the classical state-space averaging technique is not suitable for these converters, inductor current ripple averaging technique is utilized for the controller design. The circuit simulation is performed in Matlab/Simulink. The digital controller is realized using the Vertex 5/FPGA in Labview/CompactRIO module. Simulation and experimental results are presented to validate the controller performance.

The author has contributed to the simulation model development and article writing. He a has major contributions in the hardware development, the controller implementation and the testing.

Paper III

Discontinuous conduction mode of a three-level boost DC-DC converter and its merits and limits for voltage cross regulation applications

In this paper, preliminary investigation of the discontinuous conduction mode (DCM) of a TLBC is presented in order to understand the converter performance and limitations while using DCM. Mainly, the cross-regulation capability of the converter during continuous current mode (CCM) and DCM are compared using 3D plots. DCM operation can produce the same amount of cross regulation using $1/8^{th}$ inductor value, compared to the same factors during CCM operation. DCM produces unknown zero current switching periods and makes the controller design complex. It is an attractive area for further research.

The author is the main contributor for simulation and article writing.

Paper IV

Cross-Regulation Assessment of DIDO Buck-Boost Converter for Renewable Energy Application

In this paper, dual input dual output (DIDO) buck-boost converter, otherwise known as three-level buck-boost converter (TLBBC) is presented along with the new PDC method mainly for renewable grid integration applications using a grid tied TLNPC converter. Converter modes of operation, controller design, simulation and experimental results etc. are presented in detail. A comparison of cross regulation capabilities for TLBBC and TLBC converters are also included in this paper.

The author is the main contributor for the simulation, experiment and article writing.

Paper V

Analysis of Three-level Buck-Boost Converter Operation for Improved Renewable Energy Conversion and Smart Grid Integration

In this paper, preliminary analysis of a TLBBC converter modes of operation and control possibilities are presented. The complete operating range analysis of the converter is included for the combined buck-boost action and voltage balancing effects to understand its suitability for various applications.

Author is the main contributor for the simulation and article writing.

Paper VI

Contour-Based Dead-Time Harmonic Analysis in a Three-Level Neutral-Point-Clamped Inverter

In this paper, the authors present a comprehensive numerical analysis of dead-time effects on the output voltage of a three-level neutral-point clamped (NPC) inverter. Closed-form expressions of inverter phase voltage harmonics for phase opposition disposition (POD) PWM are derived based on the double Fourier series approach and modified contour plots. The harmonic spectra

from numerical evaluations, simulations, and experiments for natural sampling (NS), symmetrical regular sampling (SRS), and asymmetrical regular sampling (ARS) are compared to validate the mathematical models.
The author is the main contributor for the experimental testing of different PWM and sampling techniques used for the deadtime analysis.

Paper VII

Synchronous Current Compensator for a Self-Balanced Three-Level Neutral Point Clamped Inverter

In this paper, a synchronous current control method for a three-level neutral point clamped inverter is presented. Synchronous reference frame control based on two decoupled proportional-integral (PI) controllers is used to control the current in direct and quadrature axes. A phase disposition pulse width modulation (PDPWM) method in regular symmetrical sampling is used for generating the inverter switching signals. The simulation of closed-loop control is done inMatlab/Simulink and control is implemented in FPGA using Labview/CompactRio. The results show that the control action is reliable and efficient for the load current control.

The author contributed to the simulation and was the major contributor for the hardware development and testing.

Paper VIII

DC-Link Stress Analysis for the Grid Connection of Point Absorber Type Wave Energy Converters

In this paper, analysis and comparison of the DC-link stresses in the converter systems used for grid coupling the wave energy converters (WECs) is described for two cases - a single and three collective units of WECs. The AC/DC/AC converter system includes a conventional uncontrolled three-phase rectifier, a DC/DC converter to boost the DC-link voltage and an inverter with RL load. Matlab/Simulink based system simulation is used for the analysis. The analysis mainly shows that multiple WECs and active control strategies can reduce the stress in the DC-link and can also improve the overall system performance.

The author is the main contributor for the simulations and also helped with article writing.

Paper IX

Interconnection Strategies of Point Absorber Type Wave Energy Converters and Rectifier Units

Direct-driven point absorber type tubular wave energy converters, reflect the random nature of wave energy input to its output voltage waveform. The better conditions in the generator output stage are the first step that allows the reduction in the need of complicated power conversion system. This work presents the analysis and comparison of two important interconnection strategies of

WEC-rectifier units - Parallel and Cascaded interconnections. Conventional AC/DC/AC power conversion system is used in both cases. Matlab/Simulink based system simulation is utilized for the analysis. Various results and discussions about the selection of strategies are included

The author has mainly contributed to the simulations and also helped with article writing.

Paper X

Status Update of the Wave Energy Research at Uppsala University

The wave energy project at the Swedish Centre for Renewable Electric Energy Conversion at Uppsala University initiated its offshore experiments at the Lysekil Wave Energy Research Site in 2006. The aim of this paper is to present a status update of the Lysekil project. The presented material includes both theoretical and experimental research developments achieved by the wave energy group in Uppsala University.

The author has contributions in Section II, part G and also Section III, part E of the experimental results.

Paper XI

Development of Power Electronics Based Test Platform for Characterization and Testing of Magnetocaloric Materials

In this work, a new approach for characterization of the magnetocaloric materials is presented, with the main focus on a flexible and efficient power electronic based excitation and a completely static test platform. It can generate a periodically varying magnetic field using superposition of an ac and a dc based magnetic field. The scale down prototype uses a customized single-phase H bridge inverter with essential protections and an electromagnet load as actuator. The preliminary simulation and experimental results show good agreement and support the usage of the power electronic test platform for characterizing magnetocaloric materials.

The author is the main contributor for the design and development of the power converter part and contributed to the article writing as well.

[*This paper has only minor contribution in this thesis*]

Paper XII

Kalman Filter Based Grid Synchronization in Stationary Reference Frame

This paper includes the preliminary analysis of stationary reference frame based Kalman filter (SRF-KF) for grid synchronization of three-phase systems. Regular methods in literature uses ABC reference frame which needs three Kalman filter blocks. The stationary reference frame method decreases the computational complexity by reducing the Kalman filter requirement to two. The capability of the Kalman filter is examined in MATLAB. The digital implementation of the algorithm is done in Labview/FPGA. The result shows that the proposed method provides an accurate and reliable synchronization for both balanced and unbalanced grid voltages.

The author has main contributions in simulations and experiments.
[*This paper is ready for submission and has only minor contribution in this thesis*]

12 Acknowledgements

I would like to thank SweGRIDs for funding this research project and also supporting all the activities during my PhD. Special thanks to European Institute of Innovation and Technology (EIT) and their Knowledge and Innovation Community (KIC) InnoEnergy for providing all the added value activities, mobility support and training. Thanks to Mathias Hamberg, the InnoEnergy officer at UU for your tremendous support and motivation throughout the PhD school time. Thanks to all other officers and friends in InnoEnergy all over Europe for your support and encouragement.

Special thanks to Prof. Sasi K Kottayil, Prof. Rajeev Thottappillil, Prof. Nathaniel T. and Prof. Konstantinos K. for their support and guidance.

Thanks to all my previous colleagues and friends in Siemens AG, Corporate technology, Power Electronics group for their great support during my research mobility time in Germany. Many thanks to my manager Sebastian Nielebock and Gopal Mondal for your guidance and tremendous support all the time.

My heartfelt thanks to my supervisor Prof. Mats Lejon for giving me all the freedom and motivation during my PhD time and making sure that I evolve as an independent researcher at the end of my PhD. Many thanks to my second supervisor Prof. Jan Isberg, for always helping me with everything whenever I needed.

Special thanks to my friend and office mate Markus Gabrysch for his wonderful support and guidance throughout my PhD time and also for making my life in Uppsala a lot easier. Many thanks to my pervious power electronics colleague and friend Jelena Loncarski for all the works we have done together. Thanks a lot to Venu for all the interesting discussions we had together.

Division of Electricity, Uppsala University has made my PhD time a wonderful experience to remember forever. I would like to thank all my colleagues in the wave group for their great support during my PhD time. Special thanks to all the administrative staffs including Ingrid, Maria I & II, Gunnel and all others for your great support. Special thanks to Thomas for always supporting all my computing and other IT challenges. Many thanks to Ulf for helping me and teaching me all the mechanical hardware works at the workshop.

Many thanks to Uppsala Malayalees and other friends for making our Uppsala life wonderful.

Last but not the least, my wife Remya, my son Aagney and our Parents for understanding and supporting me always in my life.

13 Svensk sammanfattning

Förnybar elgenerering är ett växande område med målet att ha en ren och hållbar framtid för elektrisk energi. Kraftelektronik spelar en avgörande roll för inkopplandet av förnybar energi på det gemensamma elkraftnätet. Idag används vanligtvis två-stegs-omriktare för ändåmålet, men med en alltmer komplicerad och varierande energikälla, såsom vågkraft, ställer det högre krav på omriktarens kapacitet att anpassa elektricitetens vågform enligt gällande krav för elkraftnätet. Den här avhandlingen avser att tackla dessa problem med ett förbättrat kraftelektronik-system baserat på smarta fler-stegs-omriktare med realtidskontroll via Field-Programmable-Gate-Array (FPGA). Arbetet som presenteras innehåller design och optimering av ett nytt system, simuleringar och experimentell data för nätkoppling av vågkraftsaggregat.

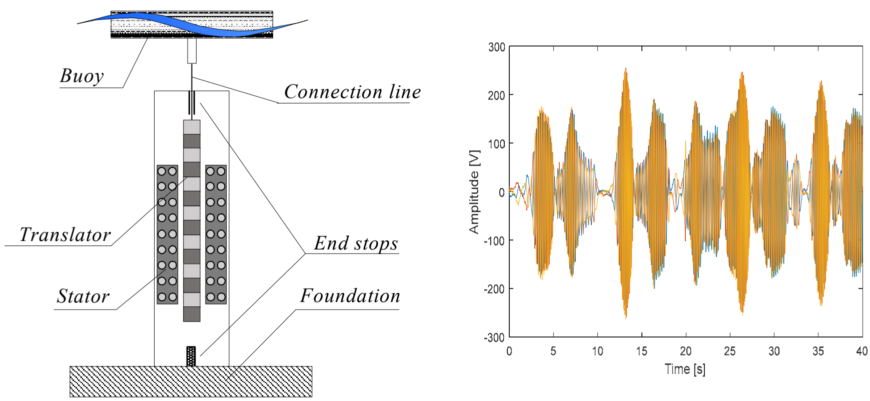


Figure 13.1 Till vänster: Direkt-driven linjärgenerator utvecklad på Uppsala universitet. Till höger: Typisk utspänning från en linjärgenerator.

Avdelningen för elektricitetslära vid Uppsala universitet har tillsammans med avknoppningsföretaget Seabased AB utvecklat ett unikt koncept för extrahering av elektricitet från vågor. Den är baserad på konceptet med distribuerade punktabsorberande bojar i en vågkraftspark där varje punktabsorberande boj är kopplad till en linjär permanentmagnetiserad generator placerad på havsbotten, se övergripande bild av konceptet till vänster i Figure 13.1. Vågornas variation av position medför att utspänningen från varje enskild generator varierar i både amplitud och frekvens, se den högra bilden i Figure

13.1. Konventionella omriktare har begränsad förmåga att hantera dessa variationer, och där kommer smarta fler-stegs-omriktare med större kontroll och längre intervall av kontroll av inkommande spänning in i bilden.

Den här avhandlingen fokuserar på tre typer av omriktare med nya ”pulse-delay-control”-metoder som ska uppnå kraven för nätanslutningen. Först likriktas den inkommande växelspänningen från generatorn via diodbryggan och antingen en tre-stegs Boost dc-dc omriktare eller en tre-stegs Buck-Boost dc-dc omriktare. Därefter transmitteras elen via en likströmskabel till en tre-stegs neutralpunktsklämd växelriktare (three-level neutral point clamped inverter) placerad på land. Avhandlingen presenterar också ihopkopplings-strategier för att öka stabiliteten på likströmskopplingen till land. Kontroll av den inkommande effekten från generatorerna och spänningsreglering på likströmskabeln sköts via dc-dc omriktare, och nätkopplingen med ström-kontroll styrs av växelriktaren. Systemdesign, simuleringar, topologi, hårdvaruutveckling och testresultat presenteras. Gränssnittet för nätkopplingen presenteras i Figure 13.2.

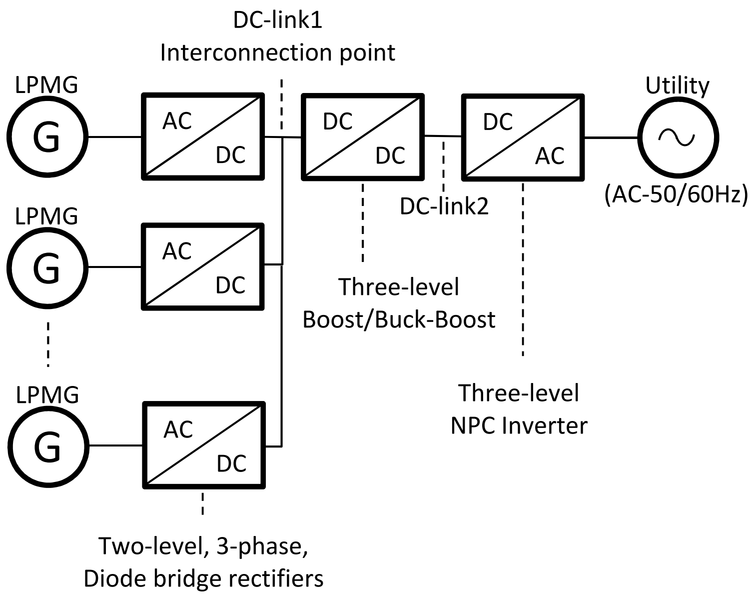


Figure 13.2 Block-diagram över fler-stegs omriktarna, likströmskopplingen till land och nätkopplingen av vågkraftsgeneratorerna.

De smarta FPGA kontrollerna med kommunikations-gränssnitt gör systemet mer flexibelt och anpassat för framtidens smarta nät. Framstegen som gjorts i varje del av systemet diskuteras för att ge en inblick i hur systemet kan komma att utvecklas vidare. Sist men inte minst presenteras en direkt AC-AComriktartopologi baserad på en modulär fler-stegs-omriktare med medföljande diskussion om hur den påverkar systemet och framtida trender i detta viktiga område.

Desto fler förnybara energikällor som kopplas in på nätet, såsom tidvatten, vågkraft, vindkraft, strömkraft och solkraft ställs högre krav på kraftelektroniken som levererar elen till nätet. För att klara detta behövs bättre förståelse och utveckling av nätkopplingen. Det finns två sätt att angripa problemet på; antingen genom att fokusera på utvinningen av energin från varje generator, som har sina begränsningar, eller genom att fokusera på den slutgiltiga kopplingen mot nätet. Den här avhandlingen har inriktats på gränssnittet mot elnätet. Generellt måste både delarna samarbeta för att optimera energiutvinningen och samtidigt kunna garantera elkvalitén som levereras till nätet.

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