

**Modulation and Fault Control of Three-phase Dual
Active Bridge Converter for Breaker-less DC Microgrid
Protection**

BY

Hamed Bin Qadhi

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

Electrical Engineering

May 2022

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Hamed Bin Qadhi** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ELECTRICAL ENGINEERING**.



Prof. Mohammed Ali Abido
(Advisor)



Dr. Abdallah Al-Ahmari
Department Chairman



Dr. Aboubakr Salem
(Co-Advisor)



Prof. Suliman Saleh Al-Homidan
Dean of Graduate Studies

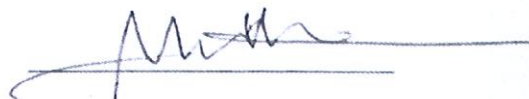


Dr. Mahmoud Kassas
(Member)

Date



Dr. Muhammad Khalid
(Member)



Dr. Mohamed Ali Hassan
(Member)

© Hamed Bin Qadhi

2022

|This work is dedicated to my beloved family |

ACKNOWLEDGMENTS

This thesis is written to fulfill the master's degree in the electrical engineering department at King Fahd University for Petroleum and Minerals. Many people have kindly supported me during this time, and I want to express my genuine gratitude and appreciation to them.

First of all, I would like to thank KFUPM and its EE department for offering me a master's position and providing all the necessary environment and facilities for a successful and insightful experience.

Also, I would like to sincerely thank my master's advisor and co-advisor Prof. Mohammed Abido and Dr. Abubakr Salem for their helpful advice and compassionate support for my work, as well as their willingness to share their vast knowledge and expertise. I would also thank my thesis committee members Dr. Mahmoud Kassas, Dr. Mohamed Hassan, and Dr. Muhammad Khalid for their genuine interest in my work and for graciously being co-examiners for my master thesis defense. I appreciate them taking the time to carefully read my thesis and provide me with helpful and informative criticism.

I would also like to thank my mentor Dr. Md Ismail for his priceless support and guidance throughout the validation process including MATLAB simulation, Real-time digital simulator (RTDS), and experimental work. Dr. Ismail is a great gentleman and having him around increased my confidence and passion in our research area.

Furthermore, I thank Hadramout establishment for human development lead and represented by Eng. Abdullah Ahmed Bugshan for the constant support since my first high school days. He always treated me as a son and he is there for me in my happy and hard times.

Additionally, I thank all my friends and colleagues with whom I had very joyful and unforgettable moments.

Saved for last, I'd like to express my deepest thanks to my parents, who have always encouraged me to travel and supported me since I was a child. I'd also like to express my gratitude to my wife, for her frequent encouragement and support. I would also thank my entire family who was my biggest motivation during the entire period. Without all of you, this effort would not be feasible.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS	VI
LIST OF TABLES.....	IX
LIST OF FIGURES.....	X
LIST OF ABBREVIATIONS.....	XII
NOMENCLATURE	XIV
ABSTRACT	XVI
ملخص الرسالة	XVII
CHAPTER 1 INTRODUCTION.....	1
1.1 Motivation	1
1.2 Thesis Objectives	4
1.3 Thesis Contributions	5
1.4 Thesis Organization.....	5
CHAPTER 2 LITERATURE REVIEW	7
2.1 DC faults.....	7
2.1.1 Capacitor discharge stage	9
2.1.2 Cable discharge stage.....	9
2.1.3 Grid-side current.....	10
2.2 DC microgrid protection challenges.....	10
2.2.1 Non-radiality of DC microgrids	10

2.2.2	The high rising rate of fault currents	10
2.2.3	Circuit breakers	11
2.2.4	Fault current value variation	11
2.3	Protection methods in DC microgrids	11
2.3.1	Current and voltage measurement-based protection	11
2.3.2	Current Derivative Protection	12
2.3.3	Directional protection	12
2.3.4	Differential protection	13
2.3.5	Distance protection	13
2.3.6	Traveling wave-based protection	14
2.3.7	Deep learning-based protection	15
2.4	Fault current interception schemes	16
2.4.1	Breaker-based methods	16
2.4.2	Breaker-less-based methods	18
CHAPTER 3 EXISTING MODULATION METHODS OF THE THREE-PHASE DUAL ACTIVE BRIDGE		20
3.1	Single Phase shift	20
3.1.1	Operating principle	20
3.1.2	Under fault condition analysis	23
3.2	Asymmetrical Duty Cycle Control	23
3.2.1	Operating principle	23
3.2.2	Three-phase triangular current modulation buck mode (TCM3-Buck)	23
3.2.3	Under fault condition analysis	25
3.3	Space-Vector-based Asymmetrical Duty-Cycle Control	25

CHAPTER 4 PROPOSED MODULATION METHODS FOR FAULT RIDE-THROUGH	27
4.1 Variable Duty Cycle Single Phase Shift Modulation	27
4.1.1 Operation Principle	27
4.2 Modified Asymmetrical Duty Cycle Modulation for Fault Control	31
4.2.1 Operation Principle	31
CHAPTER 5 RESULTS AND DISCUSSION	37
5.1 Simulative Verification	37
5.1.1 Single Phase shift	37
5.1.2 Variable Duty Cycle Single Phase Shift Modulation	41
5.1.3 Modified Asymmetrical Duty Cycle Modulation for Fault Control	45
5.2 Experimental Verification	50
5.2.1 Single Phase shift	56
5.2.2 Variable Duty Cycle Single Phase Shift Modulation	58
5.2.3 Modified Asymmetrical Duty Cycle Modulation for Fault Control	60
5.3 Comparison of simulation and experimental results	62
5.4 Results comparison and discussion	66
CHAPTER 6 CONCLUSION & FUTURE WORK	68
REFERENCES	70
VITAE	80

LIST OF TABLES

Table 1.1: DC microgrid Architectures.	3
Table 2.1: Comparison of DC protection methods	15
Table 2.2: DCCBs comparison	18
Table 5.1: Simulation Parameters of the three-phase DAB Converter	37
Table 5.2: Experimental Parameters of the three-phase DAB Converter	55
Table 5.3: Comparison of the control methods of the three-phase DAB.....	67

LIST OF FIGURES

Figure 1.1 DC microgrid diagram.....	2
Figure 2.1 Diagram for a DC microgrid at fault.	8
Figure 2.2 DC fault current waveforms for VSC-based and SST-based DC microgrids [25].	8
Figure 2.3 equivalent circuits for a PP DC fault, (a) Capacitor discharge stage, (b) Cable discharge stage, (c) Grid-side stage.....	8
Figure 3.1 three-phase DAB converter diagram [96]	20
Figure 3.2 three-phase DAB DC-DC converter schematic.....	22
Figure 3.3 ZVS region in SPS modulation for $0 \leq \phi \leq \pi/3$ [97]	22
Figure 3.4 three-phase DAB converter switching states, AC voltages and primary AC current operating with the TCM3- Buck	24
Figure 3.5 Voltage vectors of FRT-Buck method [93].....	25
Figure 3.6 three-phase DAB converter switching states, AC voltages and primary AC current operating with the FRT- Buck.....	26
Figure 4.1 three-phase DAB converter switching states, AC voltages and primary AC current operating with the VDCSPS.....	28
Figure 4.2 VDCSPS control flow chart	30
Figure 4.3 three-phase DAB converter switching states, AC voltages and primary AC current operating with the MADCC	33
Figure 4.4 MADCC control flow chart.....	36
Figure 5.1 SPS DC output voltage and current U_s & I_{out} at normal condition.....	38
Figure 5.2 SPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at normal conditions	39
Figure 5.3 SPS load angle ϕ at normal conditions	39
Figure 5.4 SPS DC output voltage and current U_s & I_{out} at fault condition.....	40
Figure 5.5 SPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at fault conditions	40
Figure 5.6 SPS load angle ϕ at fault conditions	41
Figure 5.7 VDCSPS DC output voltage and current U_s & I_{out} at zero-voltage fault	42
Figure 5.8 VDCSPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at zero-voltage fault.....	42
Figure 5.9 VDCSPS load angle ϕ at zero-voltage fault	43
Figure 5.10 VDCSPS DC output voltage and current U_s & I_{out} at 0.1 voltage ratio fault	44

Figure 5.11 VDCSPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at 0.1 voltage ratio fault.....	44
Figure 5.12 VDCSPS load angle φ at 0.1 voltage ratio fault	45
Figure 5.13 MADCC DC output voltage and current U_s & I_{out}	46
Figure 5.14 MADCC primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC}	47
Figure 5.15 regular and zoomed view of the primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase current i_{pa} for soft switching verification	47
Figure 5.16 MADCC DC output voltage and current U_s & I_{out} at 0.1 voltage ratio fault.....	48
Figure 5.17 MADCC primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at 0.1 voltage ratio fault.....	49
Figure 5.18 regular and zoomed view of the primary and secondary transformer AC voltages u_{pa} & u_{sa} , and primary side AC phase current i_{pa} for soft switching verification at 0.1 voltage ratio fault.....	49
Figure 5.19 DC Power supply	52
Figure 5.20 PE lab power converters	52
Figure 5.21 Three phase transformer	53
Figure 5.22 Resistive load.....	53
Figure 5.23 Current sensor.....	54
Figure 5.24 dSPACE DS1103 PPC Controller Board	54
Figure 5.25 Three-phase DAB circuit experimental setup	55
Figure 5.26 SPS primary and secondary transformer AC voltages u_{pa} & u_{sa} at normal condition.....	56
Figure 5.27 primary side AC phase current i_{pa} at normal condition.....	57
Figure 5.28 SPS voltage tracking performance.....	57
Figure 5.29 SPS phase a current i_{pa} at fault condition	58
Figure 5.30 Measured primary side AC phase currents i_{pa} of VDCSPS control at zero-voltage fault condition.....	59
Figure 5.31 Measured primary side AC phase currents i_{pa} of VDCSPS control at 0.1 voltage-ratio fault condition	60
Figure 5.32 Measured primary side AC phase currents i_{pa} of MADCC control at zero-voltage fault condition.....	61
Figure 5.33 Measured primary side AC phase currents i_{pa} of MADCC control at 0.1 voltage-ratio fault condition	62

LIST OF ABBREVIATIONS

AC	:	Alternative Current
ACCB	:	Alternative Current Circuit Breaker
ADCC	:	Asymmetrical Duty Cycle Control
DAB	:	Dual Active Bridge
DC	:	Direct Current
DCCB	:	Direct Current Circuit Breaker
DER	:	Distributed Energy Resource
DG	:	Distributed Generator
HIF	:	High Impedance Fault
IED	:	Intelligent Electronic Device
MADCC	:	Modified Asymmetrical Duty Cycle Control
PG	:	Pole to Ground
PP	:	Pole to Pole
PV	:	Photovoltaic
SPS	:	Single Phase Shift
SST	:	Solid-State Transformer

TCM3-Buck	:	Triangular Current Modulation Buck Mode
VDCSPS	:	Variable Duty Cycle Single Phase Shift
VSC	:	Voltage Source Converter
ZCS	:	Zero-Current Switching
ZVS	:	Zero-Voltage Switching

Nomenclature

S_{sx}	Switching state of the upper switches of phase x in the secondary bridge
S_{px}	Switching state of the upper switches of phase x in the primary bridge
U_p	Primary-side DC Voltage
U_s	Secondary-side DC Voltage
N	Transformer's turns ratio
d	Three-phase DAB voltage ratio described by $d = \frac{NU_s}{U_p}$
L_σ	Transformer's total leakage inductance referred to the primary side
φ	Load angle between the primary and secondary bridges
f	Switching frequency
i_{px}	Current passing through the primary-side of the transformer winding of phase x
u_{px}	Primary-side voltage of the transformer winding of phase x
P_x	Average transferred power for modulation method x
θ	Phase position in radians
D	Duty cycle of the modulation signal
D_p	Duty cycle of the primary bridge modulation signal

D_s	Duty cycle of the secondary bridge modulation signal
i_{sDC}	Output DC current

ABSTRACT

Full Name : [Hamed Mohammed Bin Qadhi]

Thesis Title : [Modulation and Fault Control of Three-phase Dual Active Bridge Converter for Breaker-less DC Microgrid Protection]

Major Field : [EE]

Date of Degree : [May 2022]

The need for Microgrids increases dramatically with the increased penetration of distributed generation (DGs) units in which the distribution system can be islanded from the main grid in case of grid disturbances. Also, due to the many advantages including higher efficiency and power quality, DC microgrids draw more attention than their competing AC microgrids. However, the different natural characteristics of DC systems cause many challenges in designing a proper protection scheme for DC systems. One major concern for designing protection systems for DC microgrids is the unsuitability of conventional AC circuit breakers (ACCBs) and the need for DC circuit breakers (DCCBs) which have some disadvantages including their high cost. Many researchers suggested having breaker-less architectures of DC microgrids using DC current limiters and no-load DC switches to isolate faults. Although, in many studies, three-phase Dual Active Bridge (DAB) DC-DC converters have been shown to have a very good response in fault situations. However, their conventional control methods have some drawbacks and limitations including high peak AC current value, hard switching, and reduced output DC current.

In this research, two suitable control techniques for the three-phase DAB converter for fault ride-through operation are proposed. The two methods overcome the drawbacks and limitations of the existing modulation techniques and enhance the performance of the three-phase DAB at fault situations. These approaches provide online calculation of the control parameters for reliable control of the transformer and output currents while considering soft-switching operation of the converter switches. Simulation, as well as experimental verification of the proposed schemes, are conducted. Finally, the performance of the proposed schemes is compared with the available control methods and their main features are summarized and highlighted.

ملخص الرسالة

الاسم الكامل: حامد محمد عبدالله بن قاضي

عنوان الرسالة: التعديل والتحكم في الأعطال الكهربائية لمحور الجسر النشط المزدوج ثلاثي الأطوار لحماية شبكات التيار المستمر الصغيرة بدون قواطع كهربائية

التخصص: هندسة كهربائية

تاريخ الدرجة العلمية: مايو 2022

تزداد الحاجة إلى الشبكات الكهربائية الصغيرة بشكل كبير مع زيادة تغلغل وحدات التوليد الموزع و التي يمكن فيها فصل نظام التوزيع عن الشبكة الرئيسية في حالة حدوث اضطرابات في الشبكة. أيضًا ، نظرًا للمزايا العديدة بما في ذلك الكفاءة العالية وجودة الطاقة ، تلفت شبكات التيار المستمر المصغرة مزيدًا من الاهتمام مقارنة بالشبكات المصغرة المنافسة لها. ومع ذلك ، فإن الخصائص الطبيعية المختلفة لأنظمة التيار المستمر تسبب العديد من التحديات لتصميم نظام حماية مناسب لأنظمة التيار المستمر. يتمثل أحد الاهتمامات الرئيسية لتصميم أنظمة الحماية للشبكات الصغيرة في عدم ملاءمة قواطع دوائر التيار المتردد التقليدية والحاجة إلى قواطع دوائر التيار المستمر التي لها بعض العيوب والتي أبرزها تكلفتها العالية. اقترح العديد من الباحثين وجود بنيات خالية من قاطع التيار لشبكات التيار المستمر الصغيرة باستخدام محددات التيار المستمر ومفاتيح التيار المستمر غير المحملة لعزل الأعطال. على الرغم من أنه في العديد من الدراسات ، فقد ثبت أن محولات التيار من مستمر إلى مستمر ذات الجسر النشط المزدوج ثلاثية الأطوار لها استجابة جيدة جدًا في حالات الأعطال. ومع ذلك ، فإن طرق التحكم التقليدية لديها بعض العيوب والقيود بما في ذلك القيمة القصوى العالية للتيار المتردد ، والتبديل العسير ، وقلة التيار المستمر الناتج.

في هذا البحث ، تم اقتراح تقنيتي تحكم مناسبتين لمحور الجسر النشط المزدوج ثلاثي الأطوار للركوب أثناء الأعطال. تتغلب الطريقتان على عيوب وقيود تقنيات التحكم الحالية وتعززان أداء الجسر النشط المزدوج ثلاثي المراحل في حالات الخطأ. توفر هذه الأساليب حسابًا سريعًا أثناء التشغيل لمعاملات التحكم لتحكم موثوق به في المحولات والتيارات الناتجة مع مراعاة عملية التبديل الناعم لمفاتيح المحول. أيضًا تم التحقق من فاعلية الطريقتين المقترحتين عن طريق إجراء المحاكاة بواسطة برنامج ماثلاب وكذلك التحقق التجريبي عن طريق بناء نموذج مصغر للنظام باستعمال الأجهزة والادوات المتوفرة في مختبر الطاقة. أخيرًا ، تم مقارنة أداء المخططات المقترحة مع طرق التحكم المتاحة وتلخيص مميزاتا و عيوبها الرئيسية وإبرازهما.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Generally, DC power microgrids outweigh AC microgrids in many aspects, including efficiency, complexity level, cost, power quality, safety, and the ratio of transferred power [1]. Considering the efficiency point, DC microgrids are more efficient for two reasons. The first one is the lower number of conversion stages which will reduce the amount of power losses. In AC microgrids, the power generated from the AC distributed generators (DGs) (e.g. wind turbines) goes through AC-DC-AC conversions to be connected to the main AC bus and the power from the DC DGs (e.g. solar arrays) must be converted from DC to AC. However, DC DGs can be connected easily to the DC bus in DC microgrids, while a single AC-DC conversion stage is needed for the AC DGs [2]. The other reason is the skin effect in AC systems, which increases wire resistance by allowing the current to flow in the outer edge and reducing the actual cross-sectional area. Consequently, it increases the power losses by 15-20% or more depending on the cable's cross-sectional area [3]–[5]. In addition, DC microgrids have less complexity level due to the absence of reactive power and frequency and their regulations as well as the elimination of the synchronization problems [6]. Moreover, a lot of distributed energy resources (DERs), including photovoltaic (PV) and loads such as electric vehicles (EVs), are originally DC systems. The lower cost of DC microgrids is a result of the higher efficiency, power transfer capacity, as well as reduction in conversion stages [7]. Also, the absence of the skin effect allows the DC grid to use smaller wires for the same current value and reduces the cost even more. At the point of safety, DC systems cause lower damage to the human body than AC system discharges [8], [9].

A typical DC microgrid consists of DERs, and DC loads all connected to the main DC bus. Also, the AC grid is connected to the DC microgrid using a power electronic converter. Figure 1.1 shows a DC microgrid diagram that illustrates that the power system is not radial, and the power flow is bidirectional. Medium and low voltage DC microgrids can be found in shipboard, control, telecommunication, and residential systems [10].

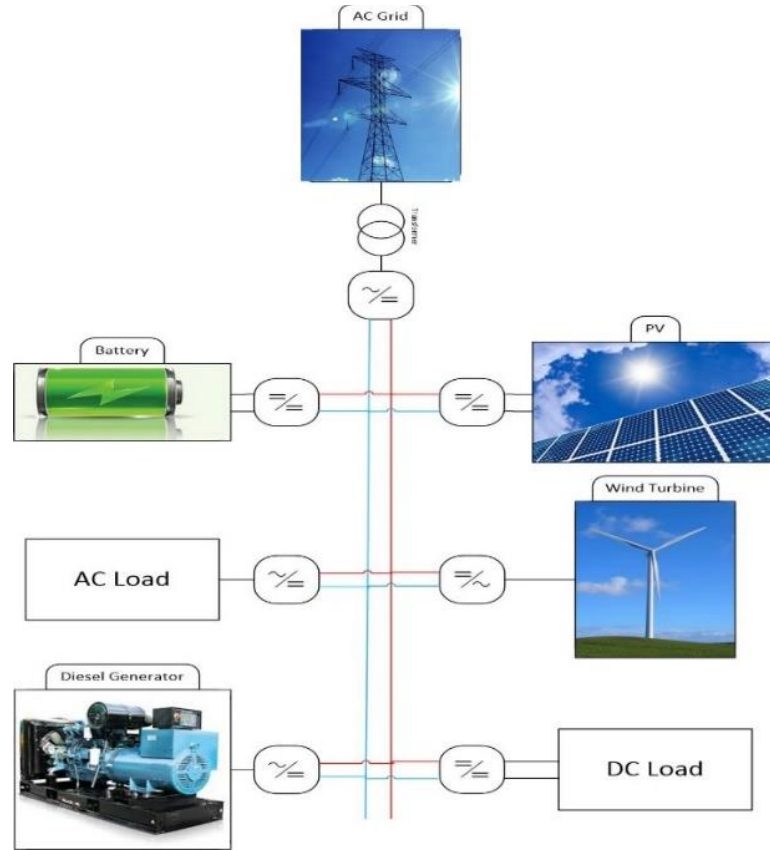


Figure 1.1 DC microgrid diagram

Based on the voltage polarity and levels, DC microgrids are classified into unipolar and bipolar DC systems. In the unipolar DC system, power flows at only one fixed voltage level via two wires where sources, and loads are connected to these positive and negative voltage wires. On the other hand, the bipolar system provides three different voltage levels (positive to ground, negative to ground and positive to negative voltage levels) only by adding the neutral wire. The higher reliability of the bipolar configuration is a major advantage as DG faults do not force an entire shutdown and power can still flow through the un-faulted pole and neutral wires [11]–[13]

DC microgrids are also classified based on their architecture. These types of configurations illustrate the connection options between the AC grid and the DC microgrid. The first type is the radial architecture in which the AC grid and the DC microgrids are interfaced in a single point, and power flows in only one path and direction. The second type is the ring-bus DC microgrid which has more than one path for the power flow and the connection between the AC grid and the DC microgrid components.

Table 1.1: DC microgrid Architectures.

Architecture Type	Pros	Cons	Applications
Radial	• Simple • In multi-bus system, buses can share power. • Low power loss.	• Very low reliability (especially when buses are connected in series) • Low selectivity	• Residential buildings
Ring	• Reliable • Higher selectivity in case of faults	• High dependency on the AC grid	• Modern residential buildings • Industrial facilities
Interconnected	Mesh	• Very reliable	• Complex design and operation • HVDC systems • Underground urban sub-transmission • Power distribution
	Zonal	• Highest reliability • Several power paths and higher selectivity	• Shipboard systems

The last type of DC microgrids configuration is the interconnected architecture where the DC microgrid is being connected to the AC grid in more than one connection point. Two different configurations are distinguished within the corresponding architecture, which are the mesh and zonal interconnected DC microgrids. The mesh configuration, also called the multi-terminal configuration, is similar to the ring architecture except for the higher number of AC supplies. However, in the zonal architecture, the DC microgrid is divided into several zones in that each sub-microgrid is supplied from two DC buses [14]–[16]. The different advantages, drawbacks, and applications of each architecture of DC microgrids are illustrated in Table 1.1.

Despite these advantages, many challenges are associated with the development of proper protection systems for DC microgrids. Due to the different characteristics between the two power systems (AC and DC), the protection methods and protection devices are not the same. Power systems must be effectively protected in that faults must be detected, located, and isolated within a specific time to avoid losing any system component. In addition, DC microgrids have many converters that are very sensitive components and need faster protection schemes.

Protection of power systems is critical to ensure a reliable system which is the main purpose of introducing microgrids. Hence, providing a proper protection system for microgrids is a prior requirement [17], [13]. Microgrids have different characteristics from conventional distribution systems, which are passive and radial networks. Conventional power systems are usually protected using fuses, reclosers, and over-current relays, which monitor the passing current and open the circuit when measuring a current higher than a pre-set threshold [18] [19].

1.2 Thesis Objectives

This thesis mainly aims to design new breaker-less protection strategies for three-phase DAB-interfaced DC microgrids. The proposed protection schemes will be based on proper control of the three-phase DAB DC-DC converter to limit and regulate fault currents. The proposed technique shall be independent of the fault type and configuration of the DC microgrid. Simulation validation will be carried out on the proposed protection schemes using MATLAB Simulink. Furthermore, the proposed method will be verified experimentally using the available equipments at the KFUPM power laboratory.

The thesis objectives can be summarized as follows:

Objective 1: Simulating the conventional and available fault control strategies for three-phase DAB for breaker-less DC microgrids using MATLAB Simulink software and comparing them to highlight the advantages and drawbacks of each scheme.

Objective 2: Developing new and better modulation and fault control strategies for the three-phase DAB to enable having breaker-less DC microgrids.

Objective 3: Validating the proposed control strategies using MATLAB Simulink software.

Objective 4: Implementing the proposed control strategies experimentally using the available equipments at the KFUPM power laboratory.

1.3 Thesis Contributions

The three-phase DAB dc-dc converter, which is used as a power-electronics building block in intelligent dc substations, is the focus of this research. Despite the fact that this three-phase DAB converter has many advantages, there are still some limits and gaps in the state-of-the-art control techniques when dealing with fault conditions including the high peak transformer AC current, low output current delivery, and hard switching. Therefore, the main contribution of this thesis is developing an optimized control technique that has no such drawbacks.

Firstly, a new modulation strategy, named variable duty cycle single phase shift (VDCSPS), was proposed. This method can effectively control both the output and transformer currents by controlling the duty cycle of the modulation signals and the load angle between the primary and secondary.

Another and more sophisticated control method named modified asymmetrical duty cycle control was proposed. This technique has three independent control parameters which are the duty cycles of the primary and secondary bridges as well as the load angle between the two bridges. This increase in control variables increases the controllability and flexibility of the converter. Both the output and transformer currents are effectively regulated, and soft switching operation can also be realized.

1.4 Thesis Organization

Aiming to achieve the aforementioned goals individually, the thesis's remaining chapters are ordered as follows.

Chapter two presents a comprehensive review on protection of DC microgrids, firstly, the consecutive stages of DC faults are discussed and analyzed. Then, the challenges facing the implementation of reliable protection schemes for DC microgrids are explained. After that, the existing protection methods to overcome the discussed challenges are classified and the advantages and disadvantages of each technique are highlighted. The last section in this chapter discusses the available options for fault current interruption and isolation of faulty sections of DC microgrids.

After being motivated in chapter two about the DC-DC converter-based breaker-less DC microgrids, the existing control methods of the three-phase DAB converter are explained in chapter three. The operation principle, as well as the behavior of the three-phase DAB converter under fault conditions of each modulation approach, is illustrated in details. Also,

the drawbacks and limitations of each existing control scheme when dealing with faults are discussed.

Chapter four presents two proposed modulation strategies for a better performance of the three-phase DAB when dealing with DC faults. The detailed derivation and operation principle of each proposed method are discussed in this chapter.

In chapter five, the proposed methods are validated in simulation and experimentally and compared with the most common existing modulation method. Firstly, the three-phase DAB circuit is built in a simulation software and controlled using the proposed and existing schemes. Furthermore, experimental testing of the proposed methods is carried out by a small-scale prototype of the three-phase DAB circuit. Finally, the simulation and experimental results are discussed and compared in the last section of this chapter.

In the final chapter, chapter six, the thesis work is briefly discussed. Also, the findings and contributions of this research are summarized. Furthermore, the possible future work to be done to enhance the outcomes of this research are address in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 DC faults

Having a comprehensive understanding of the fault current analysis is very vital for developing a proper protection method. Also, knowing the fault characteristics is required to coordinate relays and other protection devices [20].

Compared with AC systems, Faults in DC systems are more severe due to their lower resistance caused by the absence of the skin effect. Also, due to their simplicity and low cost, two-level voltage source converters (VSCs) are very commonly used power converters for AC to DC connection. However, these VSCs enable high fault current to pass from the AC grid. Therefore, Solid-State Transformers (SSTs) have been recently proposed to interface AC and DC systems. SSTs decrease the fault current value and prevent the AC grid from supplying fault currents occurring in the DC microgrid [21], [14]. On the other hand, this decrease in the fault current can affect the reliability of the conventional overcurrent protection techniques [22].

There are two types of faults in DC systems, pole to ground (PG) and pole to pole (PP) DC faults. PG fault is when one or both conductors get in touch with the ground, resulting in a high-impedance fault. On the other hand, PP fault occurs when the two conductors get short circuited, resulting in low-impedance fault. Therefore, PP faults are more severe and more likely to be detected. However, PG faults are more frequent than PP faults [23].

DC faults have a nonlinear behavior consisting of three different stages defined as capacitor discharge stage, cable discharge stage, and grid-side current stage. Figure 2.1 shows the circulating currents of all three stages of the DC fault while Figure 2.2 is the waveform of the cumulated fault current of all stages for both VSC-based and SST-based DC microgrids [24].

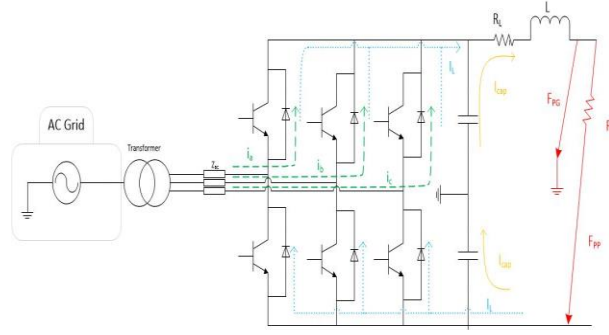


Figure 2.1 Diagram for a DC microgrid at fault

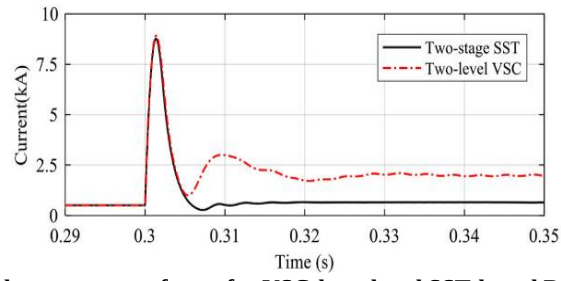


Figure 2.2 DC fault current waveforms for VSC-based and SST-based DC microgrids [25]

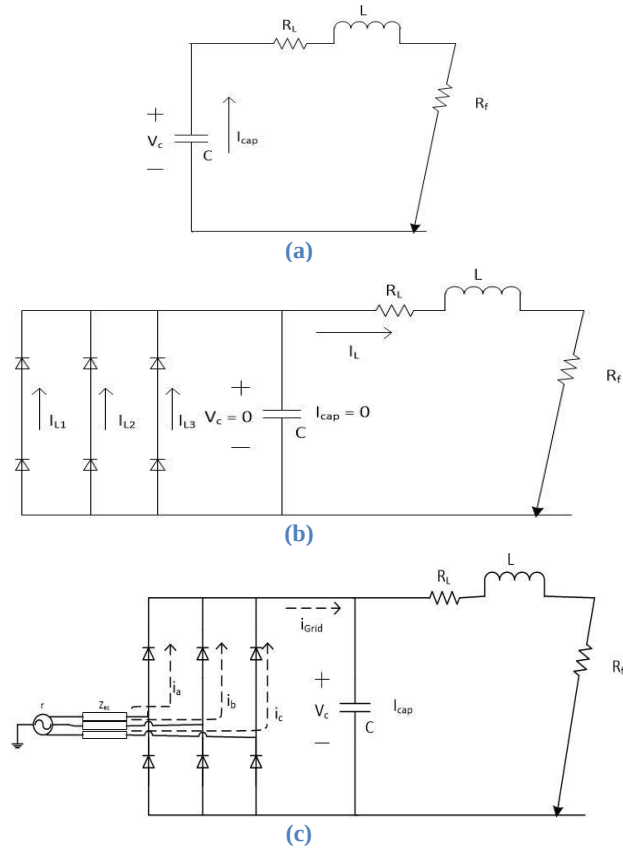


Figure 2.3 equivalent circuits for a PP DC fault, (a) Capacitor discharge stage, (b) Cable discharge stage, (c) Grid-side stage

2.1.1 Capacitor discharge stage

Momentarily after the DC microgrid the fault, the stored energy in the DC link capacitor begins to be discharged through the cable impedance. In this stage, the current oscillations can reach 100 times the VSC rated current [26]. This stage is illustrated with the equivalent circuit for PP fault shown in Figure 2.3(a) where the system dynamics can be described as:

$$\frac{d^2i}{dt^2} + \frac{R}{L} \frac{di}{dt} + \frac{1}{LC} i = 0 \quad (2.1)$$

where i is the fault current discharged from the capacitor, R the sum of both DC line resistance (R_L) and fault resistance (R_f), L is the line inductance, and C is the DC link capacitance. Using Laplace transform to solve (2.1), the fault current can be expressed as:

$$I(s) = \frac{I_L(0) \left[s + \frac{R}{L} \right]}{s^2 + \frac{R}{L}s + \frac{1}{LC}} \quad (2.2)$$

where $I_L(0)$ is the initial line current. From (2.2), it is clear that the factors affecting the fault current value are the initial line loading, capacitor size, and the fault path impedance. By factorizing the characteristic equation, the poles of (2.2) are:

$$s_{1,2} = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2} \quad (2.3)$$

where α is called the damping factor ($\alpha = R/2L$) while ω_0 is the resonance frequency ($\omega_0 = 1/\sqrt{LC}$). The behavior of current oscillations is determined by the relationship between the square of the two quantities in that the current response is under-damped if $\alpha^2 < \omega_0^2$, critically damped if $\alpha^2 = \omega_0^2$ or over-damped if $\alpha^2 > \omega_0^2$.

2.1.2 Cable discharge stage

Once the capacitor is fully discharged and its voltage reaches zero, the energy stored in the cable inductance starts to be discharged through the freewheeling diodes of the VSC. The equivalent circuit of this stage is shown in Figure 2.3(b) where the system dynamics can be described as:

$$L \frac{di_L}{dt} + Ri_L = 0 \quad (2.4)$$

Using the Laplace transform and its inverse to solve (2.4), the current response in the frequency and time domains can be expressed as:

$$I_L(s) = \frac{L I_0}{L s + R} \quad (2.5)$$

$$i_L(t) = I_0 e^{-\left(\frac{R}{L}\right)t} \quad (2.6)$$

where I_0 is the cable current at the end of the capacitor discharge stage in which the voltage across the capacitor is zero. This initial current of this stage can be very high and capable of damaging the freewheeling diodes in a very short time. Hence, the protection scheme must detect and isolate the fault before reaching this stage of the DC fault current [27].

2.1.3 Grid-side current

In this stage and as illustrated with the equivalent circuit in Figure 2.3(c), the fault current is supported by the AC grid through the VSC, which behaves like an uncontrollable full-bridge rectifier [28]. As a result, the fault current equation is:

$$i_{Grid} = i_a + i_b + i_c \quad (2.7)$$

where i_a , i_b and i_c are the unrectified parts of the three phase currents supplied by the AC grid through the freewheeling diodes.

2.2 DC microgrid protection challenges

DC microgrid protection has several challenges, which impose the necessity for critical modifications on the conventional protection systems. These challenges are listed and comprehensively discussed in this section.

2.2.1 Non-radiality of DC microgrids

One major challenge in DC microgrids protection is the bidirectionality of fault currents due to the connection of different power resources in different locations. Hence, the non-directional overcurrent relays will not identify many fault currents. Moreover, DC microgrid topology changes frequently, which may result in changing the current direction. A very effective solution for these problems is to consider all possible operational changes that may occur in the DC microgrid and adapt the relay settings accordingly [29], [30].

2.2.2 The high rising rate of fault currents

DC microgrid faults have a high rising rate because of the low resistance of the line, which can damage the different components in the DC microgrid. Although this very fast growth of fault currents enables overcurrent relays to easily and quickly detect fault currents, it can

disrupt the coordination between the relays and decreases the selectivity of the protection system of the DC microgrid [31].

2.2.3 Circuit breakers

Due to the lack of natural zero crossing in the DC current, unlike AC current, the DC current is more difficult to be interrupted and AC circuit breakers (ACCBs) are not suitable for fault current interruption in DC microgrids [32],[33]. Furthermore, due to the high rising rate of the fault current as well as the low short-circuit tolerances of the power electronic converters, fault currents have to be interrupted very fast within microseconds [34]. In order to overcome the mentioned fault current interruption challenges, DC circuit breakers (DCCBs) have been developed. However, they are very complex, and their prices can reach to dozen times that for ACCBs with the same rating voltage and current [35].

2.2.4 Fault current value variation

Another protection challenge is the change in the short circuit level. Fault current value can go up to 20-50 times higher than the rated current. However, it also can be smaller than the relay threshold setting. This remarkable change in fault current level is mainly due to changes in operating conditions and grid-connected and islanded modes of microgrid operation [36]. Due to the dependency of current-based relays on the amplitude of the fault current, the grounding system of the DC microgrid should be carefully designed for it to help relays detecting PG faults [37].

2.3 Protection methods in DC microgrids

Recently, many protection schemes have been presented to overcome the above-mentioned challenges. Some of these methods are discussed in this section.

2.3.1 Current and voltage measurement-based protection

DC overcurrent protection is designed in a similar procedure to conventional AC overcurrent protection, where fault detection is done by setting a specific threshold for the line current. In [33], the DC microgrid converters have been utilized to interrupt fault currents detected by overcurrent relays. These relays detect faults by monitoring both the line current and the capacitor voltage. The DC microgrid is divided into several protection zones to ensure selectivity and coordination among relays. However, the scheme is limited to small DC microgrids as its speed and reliability will decrease with the complexity of the DC microgrid. Another protection scheme with high speed, selectivity, and sensitivity is proposed in [38]. The method utilizes both unit-based protection and overcurrent protection

to extract the advantages of these techniques. However, the scheme could not overcome the low sensitivity of overcurrent protection for high impedance faults.

In [39], a new technique for locating faults in DC microgrids was introduced. The proposed algorithm needs only the current and voltage measurements to accurately determine the location of occurred faults with a 2% error. However, the accuracy of this technique depends on the distance and fault resistance as the error increases for far and high resistance faults.

Change in the current direction occurs very often in DC microgrids. According to [40], this issue has been addressed by adding the direction monitoring feature to conventional overcurrent relays. Yet, the proposed scheme is also unable to detect faults with high impedances that result in small current values to be recognized.

This common issue of high impedance fault identification was addressed in [41] by adding a parallel LC filter in series at each system line. Once a fault occurs, this LC circuit produces a voltage signal extracted using wavelet transform to determine the disturbance. This method is very effective for fault with resistances up to 200 Ω , but it is not fast and may not meet the fault detection time requirement.

Under voltage protection strategy can also be applied for DC microgrids, but this type of protection has poor selectivity. Thus a new protection scheme was proposed in [25] based on monitoring the DC voltage magnitude, the sign of the second derivative of the voltage, and the current rate of change (di/dt). The protection scheme was developed for an SST interfaced DC microgrid. It provided a fast and selective protection against fault with resistance up to 0.25 Ω , which can be increased by adding inductance to the DC feeders.

2.3.2 Current Derivative Protection

As discussed above, DC faults have a high rising rate which means that the current derivative is quite high. Taking this feature into consideration, fault currents can be detected very quickly. In [42], the first derivative is used to detect fault currents. In order to eliminate the dependency of the first derivative on cable length, line loading, and fault impedance which can cause false tripping, the second derivative is additionally used as a fault threshold. This problem of the first derivative is also solved using the integration of the line current as a second threshold as proposed in [43]. This research suggests a backup protection scheme in case of failure in the primary method, relays and/or breakers.

2.3.3 Directional protection

The directional protection technique is based on the idea that current direction changes at only one end of the protected feeder when the fault happens. In [44], the directional protection method was proposed and verified on a ring-type DC microgrid. The scheme

uses intelligent electronic devices (IEDs) at both ends of each segment and the least square method to estimate the fault path inductance and determine the fault current direction. This scheme provides accurate detection and location of faults. Another directional protection scheme was suggested in [45]. The scheme is very fast, with a fault detection time reaches 100 μ s. However, its dependency on communication channels reduces its reliability and increases its cost.

A superimposed current component-based directional protection scheme was proposed in [46]. Using IEDs, superimposed fault currents from both ends of the line segment were used in this method. The scheme is based on signs of the superimposed currents and their coordination to distinguish internal and external faults. The better and improved performance of this scheme compared with other unit-based protection schemes such as current directional and differential techniques is the main advantage of this approach. However, its reliability is limited to faults with less than 5 Ω resistance. In [47], a superimposed current directional protection was proposed. The superimposed component of the current is measured by an IED at each end of the protected line. This current is fed to a periodically forced harmonic oscillator which solves its equation and determines the system states to discriminate normal and fault conditions. The scheme detects fault type and direction and clears it even in high impedance faults (HIFs).

2.3.4 Differential protection

The current magnitude on the two ends of a line is measured and subtracted, and faults are detected based on the differential current value. A differential protection scheme is proposed in [48] along with a directional overcurrent protection as backup protection in case of communication failure. The protection scheme also proposes a self-healing and adaptive strategy to ensure successful system operation. The proposed scheme uses isolators to compensate for the high cost of the required communication. In [49], another differential protection scheme is proposed, which analyzes the differential current measurements and gets advantage of its characteristics to decrease the response time of fault detection of the protection scheme. The disadvantage of this scheme is the decrease in its accuracy and reliability in case of faults with high resistances. The differential protection technique was also designed and implemented in [50] to detect and locate faults in a PV-based DC microgrid. The differential protection technique provides very fast and accurate protection. However, its need for communication assets decreases its reliability and increases the protection cost of the DC microgrid.

2.3.5 Distance protection

In this method, faults are detected and located by measuring the impedance from a certain point known as the point of measurement (POM) to the fault point. The appropriate isolation device will receive a tripping signal once the measured impedance falls under a

certain distance range. In [51], faults are detected based on calculating the apparent resistance from the measured voltage to current ratio using sensors, signal conditioning, and filtering stages. The scheme is very cost effective as it uses only the power converters and segmenting contactors to measure, detect, limit, and isolate fault currents in the DC microgrid. The disadvantages of this scheme are the inability to detect high impedance faults (HIFs) as well as the low protection speed.

The HIFs problem has been addressed in [52] for high penetration of constant power loads DC microgrid. The proposed protection scheme is based on estimating the fault resistance by calculating the system power sharing. The scheme also uses the pre-fault data and current first derivative to determine the fault location. However, this method is system dependent as the relay setting varies from one system to another. Another fault resistance estimation techniques that considers HIFs is presented in [53]. The method is based on calculating the fault distance and fault resistance by sampling the current in the DC line after tripping the circuit breaker. The method is fast, accurate and can be used in both radial and mesh DC networks, it requires two protection devices for each DC line which increases its cost. In [54], a different way to estimate the fault location is presented. The method is based on analyzing the voltage resonance caused by the discharge of DC-link capacitors after occurrence of faults. The fault distance is determined after extracting the characteristics of this resonance using The Prony's method. This method does not require communication links, but it requires consistent data acquisition and accurate linearization of the RLC circuit

2.3.6 Traveling wave-based protection

When it comes to DC grids, transient-based protection algorithms are considered to be the best solution for protection systems [55]. Traveling waves are the high frequency content of the fault induced component, which carries the main fault characteristics. As a result, traveling wave-based protection schemes are reliable with a very high operation speed. This protection approach is considered one of the best solutions to detect and locate faults in high or medium voltage DC transmission systems. Still, it may not be suitable for short LVDC distribution networks [56]–[59].

Using local measurements, an ultra-high speed protection method was proposed in [60]. The approach can detect, classify, and locate faults in the DC microgrid by analyzing the waveshape of the traveling wave and estimating its time constant. The major disadvantage of this algorithm is the very high frequency of the fault current component to be analyzed, which can reach tens of MHz's. As a result, this scheme requires very expensive hardware devices. The same authors tried to address this issue in [61] by utilizing the first two subsequent traveling wave reflections to detect and locate faults in DC microgrids.

Table 2.1: Comparison of DC protection methods

Protection method	Speed	Sensitivity	Selectivity	Reliability	Cost
Current and voltage measurement-based protection	Moderate	Low/moderate	Moderate	Moderate	Low
Current Derivative Protection	High	High	Low	Moderate	Low
Directional protection	Moderate	Low/moderate	High	Moderate	Moderate
Differential protection	High	High	High	Moderate	High
Distance protection	Slow/moderate	Moderate	High	High	Moderate
Traveling wave-based protection	High	Moderate	High	Moderate	Moderate
Deep learning-based protection	Slow/moderate	Moderate	High	Moderate	Moderate

2.3.7 Deep learning-based protection

Similar to several disciplines, deep learning algorithms broke into DC systems protection and attracted many researchers, especially after the efficient performance in detecting and locating faults in AC systems. System architecture dependency and high computational intensity are the major drawbacks of this kind of protection technique [62].

In [63], an artificial neural network (ANN)-based method was suggested to identify the fault location in a PV system. The approach used direct wavelet transform to extract the features of the high frequency fault noise signal. The technique has proven accurate and robust, but it did not explore high resistance faults in addition to the intensive computing

requirement. This intensive computation problem has been eliminated in [64] by utilizing the local current measurements. However, it requires communication channels between line ends which reduces the reliability of the protection system. Another ANN-based approach was proposed in [65] for fault locating in DC distribution networks. The technique is not fast for DC systems as it requires 30 ms for fault interception.

Table 2.1 summarizes all aforementioned protection methods with their advantages and disadvantages.

2.4 Fault current interception schemes

Fault current limiting and/or interruption is the major task of the protection scheme to maintain the system stability and healthy components. As mentioned above, protection schemes applied in DC systems are required to have higher operation speed than those in AC systems due to the higher fault current rising rate and the higher number of power electronic converters.

2.4.1 Breaker-based methods

Several studies have been proposed for DC microgrid protection based on circuit breakers to isolate the faulty section. These breaker-based techniques are more reliable, selective, and can handle more fault conditions. In the following, the two types of circuit breakers, ACCBs and DCCBs, are discussed in detail:

a. ACCBs

Having the alternating behavior of the AC current leaves the ACCB with only one task, which is to open its contacts at the zero-crossing of the current. As a result, ACCBs are simpler in design and much less expensive than DCCBs [66]. In [67], VSC-based multi-terminal DC (MTDC) systems' protection technique was proposed utilizing ACCBs to cut the fault current supply. The handshaking method is used to locate the fault and then ACCBs are utilized to prevent the AC grid from supplying the fault current. Once the fault current reaches zero, a fast DC switch opens and isolates the faulty section. This method is not feasible for DC grids with DC sources and requires system de-energization, which reduces power system reliability.

b. DCCBs

Fuses can also be applied in DC systems, and they are also the simplest and most cost-effective protective devices. Along with fuses, molded case circuit breakers (MCCB) are the conventional and common protection devices in DC systems.

Although they are suitable for LV applications, the insufficient interruption speed and need for replacement are the major drawbacks of these devices [68], [69]. To overcome these disadvantages, four types of DCCBs were proposed, which are mechanical (MCB), solid state (SSCB), hybrid (HCB), and z-source circuit breakers (ZSCB).

The absence of the current zero-crossing in DC systems added more requirements from the DCCBs. DCCBs are required to create artificial current zero crossing and quickly interrupt the fault current [70], [34]. For DCCB design, many artificial zero crossing-producing approaches were proposed, including current injection, passive and active resonance circuits, as well as arcing voltage techniques.

Three main parts are what compose MCBs. A commutation circuit to create artificial zero-crossings in the fault current signal. A mechanical switch to interrupt the fault current at the first current zero-crossing. The last part of the MCBs is the energy absorber circuit, for post clearance energy absorption and dissipation. Metal Oxide Varistors (MOV) are the typical energy absorber circuits used in DCCBs. MCBs are very efficient in terms of both cost and power loss. However, the current interruption capability of these circuit breakers is very limited, and their operation time is considered to be long (30-100 ms) [71], [72].

The low-speed operation disadvantage of MCBs was solved in SSCBs by using semiconductor switches including Gate-Turn-off (GTO) Thyristor, Integrated Gate-Commutated Thyristors (IGCTs), Insulated-gate Bipolar Transistors (IGBTs), and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs). Although, such switches enable high speed interruption of fault currents, they have high conduction losses which raise the need for cooling systems that will enlarge the breaker's size and cost. These conduction losses can be reduced by utilizing Wide Band-Gap (WBG) semiconductors [73]–[77].

After knowing the advantages and disadvantages of the MCBs and SSCBs, HCBs are proposed by combining the structures of MCBs and SSCBs. As a result, HCBs have high operation speed and low power losses. HCBs mainly consist of a mechanical switch to initiate the interruption, a main semiconductor switch, and an MOV unit for power absorption and dissipation [35], [78]–[80].

ZSCBs are an improved version of SSCBs with many extra advantages, including fast turn-off, natural commutation lower cost and simple control [81]. Although ZCCBs suffer from drawbacks, such as the need for high activation current and the undesired power flows during transitions, improved and modified ZCCBs to overcome their conventional disadvantages and enhance their performance have been presented [82]–[84].

Table 2.2 summarizes the main advantages and disadvantages of the four DCCBs in terms of the main comparison categories.

Table 2.2: DCCBs comparison

DCCBs Type	Speed	Power Loss	Cost
MCB	Low (30-100ms)	Very low	Low
SSCB	High (<100 μ s)	Very high	High
HCB	High	Moderate	Very high
ZSCB	High	High	Moderate

2.4.2 Breaker-less-based methods

As mentioned above, the lack of zero-crossing in DC grids complicated the design and price of the DCCBs. Therefore, many studies have been conducted to develop breaker-less protection systems for DC networks. These kinds of strategies are based on analyzing the fault current behavior passing through the power converters connecting sources with the DC grid and designing a proper control scheme for current limiting. the faulty section is isolated using no-load tie contactors located at each line end. Two main types of the breaker-less-based methods are explained in the following:

a. Components coordination-based methods

In this type of protection systems, fault detection and isolation are achieved by proper coordination between system components. In [51], a breaker-less protection scheme was proposed for DC microgrids based on coordination between the power converters and bus segmenting contactors. In this technique, faults were detected and located by measuring the resistance at each converter and contactor. After that, the converters immediately switch to the current limiting mode enabling contactors to isolate the faulty line based on their resistance time-to-trip curves. The method is fast and effective, but it is feasible only for radial networks and low resistance faults. Also, different predefined resistance trip time curves need to be set for each contactor. These drawbacks have been overcome in [85], where the approach presented can detect, locate, and isolate short circuit and high resistance faults by properly coordinating between source converters and intelligent three tie contactor switch units (ICU). The scheme is fast and robust but vulnerable to communication failures.

b. DC-DC converters-based methods

DC-DC converters are mainly used to raise or reduce the input voltage and regulate the output signal. In addition, DC-DC converters can play a significant rule in protection of DC microgrids. By using proper control topologies and coordination with switches, DC

faults can be detected and isolated [86], [87]. Most breaker-less protection schemes operate with the following procedure:

- Once the fault occurs, converters switch to the current limiting mode to protect the DC network and enable detection and location of the fault.
- After enough time for fault detection and location, the current value is reduced to zero by proper control schemes of the converter, and the grid is de-energized
- In this stage, no-load contactor or switches associated with the faulty line open to isolate the fault.
- After faulty section isolation, the system can be restored by regular operation of converters.

DC buck converters can be designed to be intrinsically immune to faults, as suggested in [88]. In [89], the boost DC-DC converter was used to detect the fault in a few microseconds and isolate the source from the DC network. Dual active bridge DC-DC converters have many advantages when it comes to DC systems protection, including:

- Galvanic isolation of the main power source due to the input to output isolation feature of the transformer.
- Fault detection.
- Current control and limiting ability.
- Fault tolerant capacity (FTC).
- Enabling breaker-less protection schemes.

In the case of high-power applications, a dual active bridge (DAB) converter may not be a good choice for power system protection. Instead, full-bridge modular multilevel converters (MMC) with a proper control strategy can ride through DC faults and actively limit the fault current [90]. Also, MMCs can be combined with DAB modules to provide galvanic isolation between the source and the DC grid [91]. In addition, three phase DABs is also feasible for high power application. Three-phase DABs provide more advantages than the single-phase DABs, such as the higher power density, smaller size of the DC-link filter, and soft-switching operation in fault conditions. Conventional single phase shift control method of the three phase DAB has many disadvantages in fault conditions, including the high peak current, which can harm the semiconductor switches, hence space vector asymmetrical duty cycle control was suggested to enable the three phase DAB to ride through fault while realizing soft switching operation [92]–[94].

CHAPTER 3

EXISTING MODULATION METHODS OF THE THREE-PHASE DUAL ACTIVE BRIDGE

As shown in Figure 3.1, the three-phase DAB converter is made up of two three-phase bridges connected by a medium-frequency three-phase transformer. The transformer's winding configuration can be Y/Y, Δ/Δ , or Y/ Δ , which affects the three-phase DAB converter's working characteristics [95]. The three-phase DAB converter is studied in the rest of this thesis using the most widely used Y/Y linked three-phase transformer. State-of-the-art modulation techniques for three-phase DAB control are briefly introduced in the following sections:

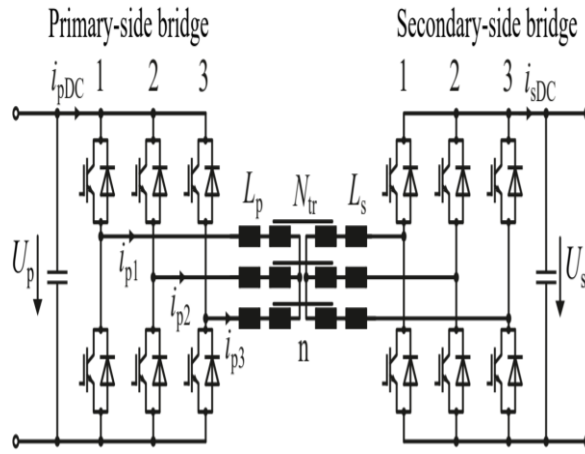


Figure 3.1 three-phase DAB converter diagram [96]

3.1 Single Phase shift

3.1.1 Operating principle

Single phase-shift is the most common modulation method for three-phase DAB control [92]. The operation principle of this method is that the two bridges are modulated with a fixed frequency and duty cycle, 50% duty cycle is used. Hence, the only control parameter is the phase shift between the modulation signals φ of the three-phase DAB. In other words, the secondary bridge is modulated with a φ shifted signal of the modulation signal of the

primary bridge. Using this load angle φ , the transferred power from the primary to the secondary sides of the three-phase DAB is controlled as:

$$P_{SPS} = \begin{cases} \frac{dU_P^2}{2\pi f L_\sigma} \left(\frac{2\varphi}{3} - \frac{\varphi^2}{2\pi} \right) & 0 \leq \varphi \leq \frac{\pi}{3} \\ \frac{dU_P^2}{2\pi f L_\sigma} \left(\varphi - \frac{\varphi^2}{\pi} - \frac{\pi}{18} \right) & \frac{\pi}{3} < \varphi \leq \frac{\pi}{2} \end{cases} \quad (3.1)$$

Where d is the three-phase DAB voltage ratio described by $d = \frac{NU_S}{U_P}$, N is the transformer's turns ratio, L_σ is the transformer's total leakage inductance referred to the primary side i.e. $L_\sigma = L_P + N^2 L_S$, f is the switching frequency.

For $|\varphi| = \frac{\pi}{2}$, maximum power can be transferred, but having $\frac{\pi}{3} < |\varphi| \leq \frac{\pi}{2}$ results in a large reactive power which affects the system's efficiency. Therefore, the magnitude of the load angle is usually kept less than $\frac{\pi}{3}$.

Depending on the switching states of the primary and secondary switches S_p and S_s , respectively, three-phase voltages are produced by each bridge representing the primary u_p and secondary u_s voltages of the transformer. These voltages has four discrete levels namely $\pm \frac{U_P}{3}$ and $\pm \frac{2U_P}{3}$ for the primary bridge and $\pm \frac{U_S}{3}$ and $\pm \frac{2U_S}{3}$ for the secondary bridge, where U_P and U_S represent the primary and secondary dc-link voltages, respectively, as shown in Figure 3.2.

Zero-voltage switching (ZVS) operation in SPS modulation occurs at the turning on operation of the switches when the corresponding anti-parallel diodes are conducting. ZVS is a very desired operation as it reduces the switching losses as well as the electro-magnetic interference noises. In SPS, the ZVS regions are shown in Figure 3.3, which are identified by the transferred power and the voltage ratio of the three-phase DAB.

Figure 3.3 shows that ZVS operation can be achieved for both primary and secondary bridges for all power levels at unity voltage ratio ($d = 1$). Furthermore, the maximum transferred power increases linearly with the voltage ratio.

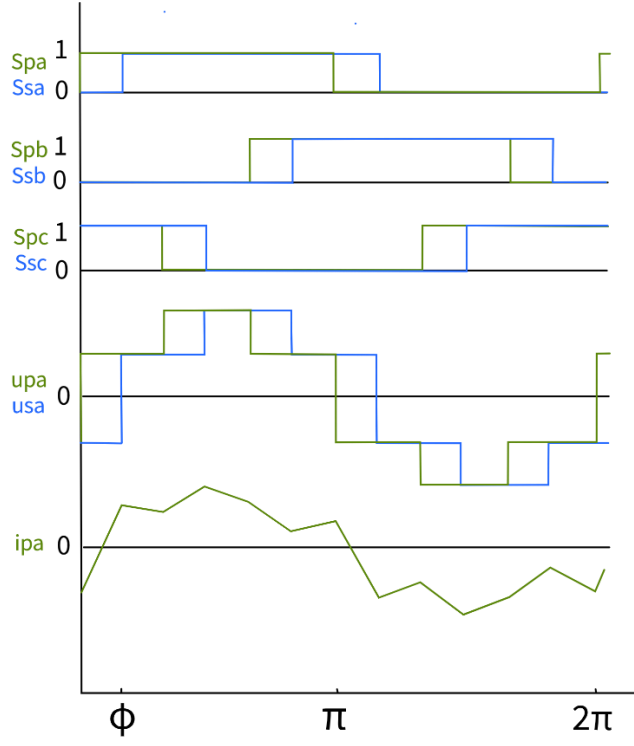


Figure 3.2 three-phase DAB DC-DC converter schematic

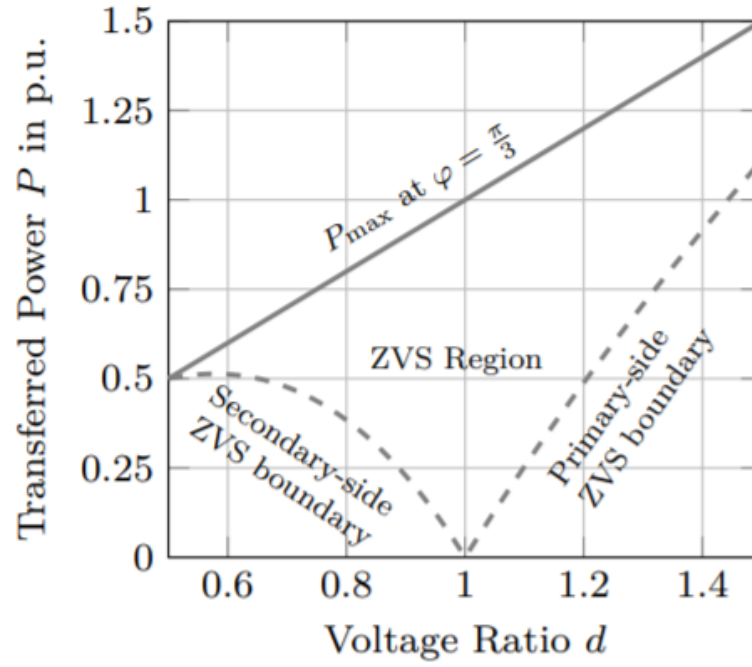


Figure 3.3 ZVS region in SPS modulation for $0 \leq \varphi \leq \pi/3$ [97]

3.1.2 Under fault condition analysis

In low-voltage or zero-voltage fault conditions, the three-phase DAB converter can still deliver the same amount of output current using SPS modulation. However, when the voltage ratio is lowered, the peak current and rms current of semiconductor devices increases considerably. Furthermore, in the low voltage-ratio state, the output current cannot be efficiently controlled by the load angle, as illustrated in (3.1). The worst-case scenario is the zero-voltage fault, in which the three-phase DAB converter's output current is independent of the load angle φ . Furthermore, switches of the secondary bridge suffer from hard-switching turn-on in low voltage-ratio settings. The associated heat stress and electromagnetic interference (EMI) disturbances have the potential to harm semiconductor devices. As a result, the SPS modulation is incompatible with dc fault ride-through (FRT) functioning.

3.2 Asymmetrical Duty Cycle Control

3.2.1 Operating principle

Asymmetrical duty cycle control (ADCC) approach was developed to expand the operating voltage ranges where soft-switching operation can be still maintained. Also, ADCC aims to minimize the rms current under light-load scenarios. This technique is based on regulating the duty cycle of the primary D_p and secondary D_s bridges ranging from 0 to one third of the switching period. D_p and D_s provide two more degrees of freedom to adjust the transformer current and transferred power, in addition to the load angle between the primary and secondary bridge [97].

ADCC approach has three different modulation modes which are the three-phase triangular current modulation buck mode (TCM3-Buck), three-phase triangular current modulation boost mode (TCM3-Boost), and three-phase trapezoidal current modulation (TZM3). TCM3-Buck is the most suitable mode for fault operations which its operation is more explained in the following section:

3.2.2 three-phase triangular current modulation buck mode (TCM3-Buck)

TCM3-Buck mode is applied in light load conditions to step down the input voltage. In this mode and referring to Figure 3.4, the primary and secondary duty cycles can be written in terms of the phase position θ as $D_p = \frac{\theta_1}{2\pi}$ and $D_s = \frac{\theta_2}{2\pi}$. Also, the angle φ represents the phase difference between the centers of the switching states of the primary and secondary bridges S_p and S_s and it is given by $\varphi = \frac{\theta_2 - \theta_1}{2}$.

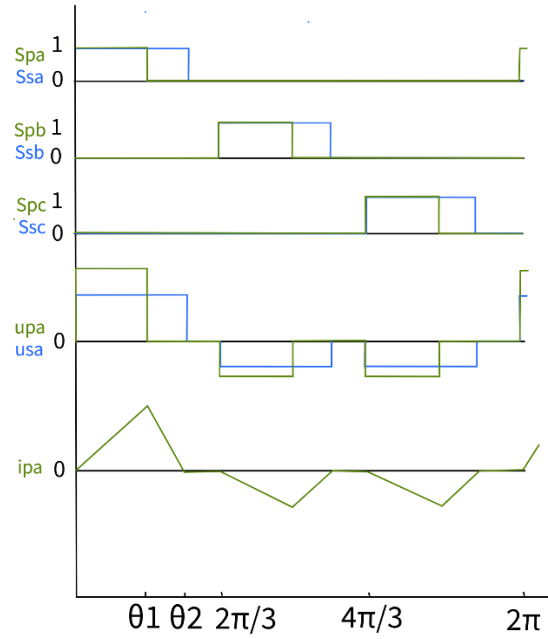


Figure 3.4 three-phase DAB converter switching states, AC voltages and primary AC current operating with the TCM3- Buck

The rms current passing through the transformer windings is obtained in terms of the load angle φ as follows:

$$i_{pa} = \frac{dU_p\varphi}{3\pi fL_\sigma} \sqrt{\frac{2\varphi}{(1-d)\pi}} \quad (3.2)$$

And the average transferred power for a lossless converter model is given by:

$$P_{TCM3-Buck} = \frac{d^2 U_p^2 \varphi^2}{\pi^2 f L_\sigma (1-d)} \quad (3.3)$$

This modulation mode provides soft switching transitions of all switches in the primary and secondary bridges except for the upper switches of the primary bridge as they have zero-voltage switching (ZVS) turn-on but hard turn-off.

3.2.3 Under fault condition analysis

As mentioned above, TCM3-Buck is the most suitable ADCC mode for fault situations. Using this modulation technique, the peak current of semiconductor devices can be regulated, and soft-switching operation can be achieved. However, and due to the proportional relation between D_p and the voltage ratio d , The maximum output current of the TCM3-Buck mode reduces considerably with the voltage ratio. This will also lead to zero output current at zero-voltage fault conditions. As a result, while the TCM3-Buck allows the three-phase DAB converter to soft-switch at a low voltage ratio, the limited output current, particularly at zero voltage, prevents it from being used for dc FRT.

3.3 Space-Vector-based Asymmetrical Duty-Cycle Control

This method was developed from the ADCC to overcome its limitations on dealing with faults and enable the three-phase DAB to ride through zero-voltage faults. The method is based on utilizing the other three voltage vectors of the primary bridge, $\vec{U}_2$, $\vec{U}_4$, and $\vec{U}_6$, that were not used in TCM#-Buck and uses only vectors $\vec{U}_1$, $\vec{U}_3$, and $\vec{U}_5$, as described in Figure 3.5. As a result, the primary duty cycle D_p increases while the soft-switching operation is still maintained. Also, the duty cycle of the secondary bridge D_s is fixed to 1/3 to maximize the DC output current [93].

Hence, in this method and in addition to the original voltage vectors of the primary and secondary bridges used in the TCM3-Buck approach, the opposite voltage vector of the primary bridge is also applied to control the transformer current in each one-third of the switching time as shown in Figure 3.6,

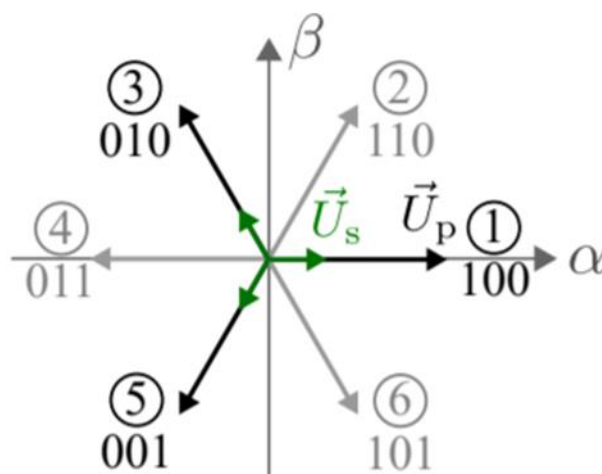


Figure 3.5 Voltage vectors of FRT-Buck method [93]

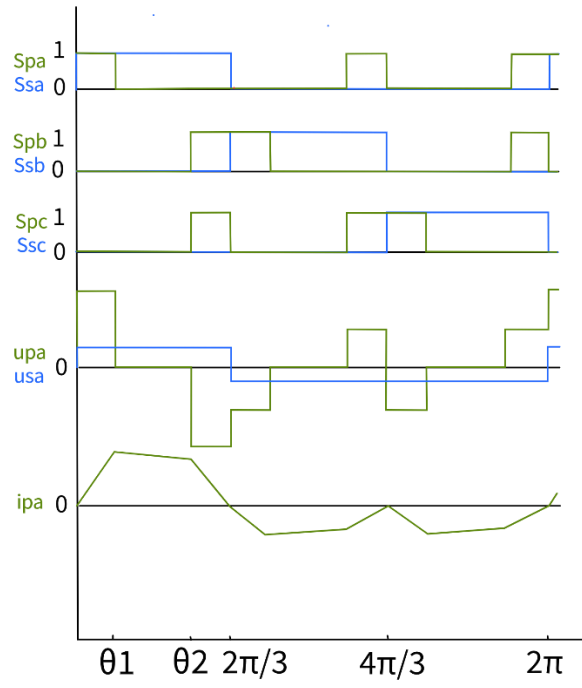


Figure 3.6 three-phase DAB converter switching states, AC voltages and primary AC current operating with the FRT- Buck

The peak value of the primary phase current is obtained to be:

$$i_{pa}(\theta_1) = \frac{dU_p\varphi}{3\pi fL_\sigma} \sqrt{\frac{2\varphi}{(1-d)\pi}} \quad (3.4)$$

And the maximum delivered power and current are given by:

$$P_{FRT-Buck,MAX} = \frac{d(1-d)^2 - U_p^2}{18fL_\sigma} \quad (3.5)$$

$$\overline{i_{sDC,max}} = \frac{(1-d^2) - U_p}{18fL_\sigma} \quad (3.6)$$

CHAPTER 4

PROPOSED MODULATION METHODS FOR FAULT

RIDE-THROUGH

4.1 Variable Duty Cycle Single Phase Shift Modulation

In this thesis, a new approach of variable duty cycle single phase shift (VDCSPS) method is proposed to control the three phase DAB current in fault conditions. Unlike the duty-cycle control described inⁱ [98]–[100], this method provides an analytical solution to the control parameters that may be calculated online with commercial digital controllers. The operation principle and theoretical derivation is illustrated in the following.

4.1.1 Operation Principle

In this modulation approach, the duty cycles of the primary and secondary bridges D are the same but have variable values for more control of the output and transformer AC fault currents. As shown in Figure 4.1, a piecewise-linear phase current is derived for $0 \leq \theta \leq \frac{2\pi}{3}$ by computing the voltage difference between the primary and secondary phase voltages as follows:

for $0 \leq \theta \leq \varphi$

$$i_{ap}(\theta) = \frac{2 U_p}{3\omega L} \theta + i(0) \quad (4.1)$$

for $\varphi \leq \theta \leq D$

$$i_{ap}(\theta) = \frac{2 U_p}{3\omega L} (1 - d)(\theta - \varphi) + i(\varphi) \quad (4.2)$$

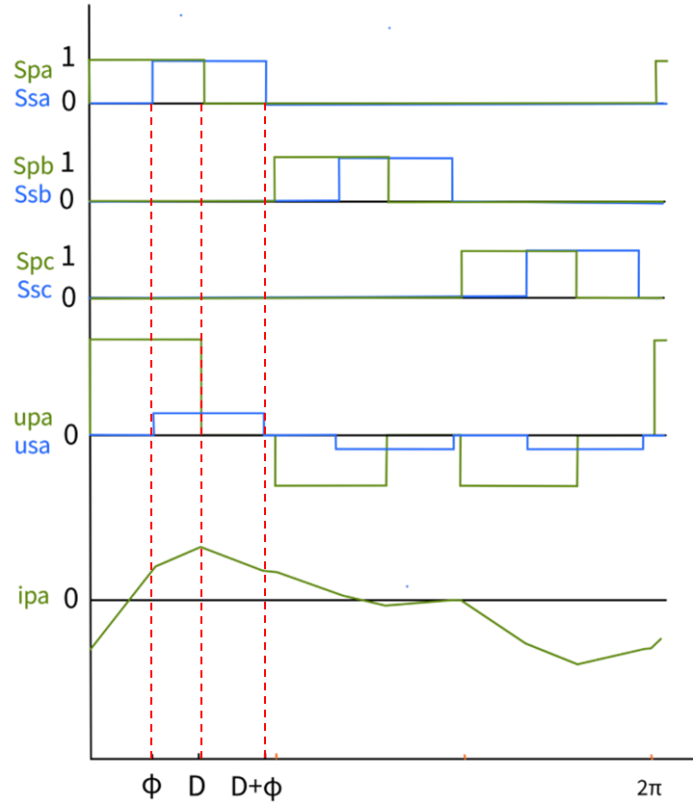


Figure 4.1 three-phase DAB converter switching states, AC voltages and primary AC current operating with the VDCSPS

for $D \leq \theta \leq \varphi + D$

$$i_{ap}(\theta) = -\frac{2 dU_p}{3\omega L}(\theta - D) + i(D) \quad (4.3)$$

for $\varphi + D \leq \theta \leq \frac{2\pi}{3}$

$$i_{ap}(\theta) = i(\varphi + D) = i\left(\frac{2\pi}{3}\right) \quad (4.4)$$

By equating $i(0) = -i\left(\frac{2\pi}{3}\right) = i(\varphi + D)$ we get:

$$i_{ap}(0) = \frac{D U_p}{3\omega L} (d - 1) \quad (4.5)$$

and after substituting $i_{ap}(0)$ in (4.1), (4.2), (4.3), and (4.5) we obtain:

for $0 \leq \theta \leq \varphi$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L}(dD - D + 2\theta) \quad (4.6)$$

for $\varphi \leq \theta \leq D$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L}(dD - D + 2\theta - 2d\theta + 2d\varphi) \quad (4.7)$$

for $D \leq \theta \leq \varphi + D$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L}(dD + D + 2d\varphi - 2d\theta) \quad (4.8)$$

for 1:1 turns ration, the transformer primary and secondary phase currents are the same i.e., $i_{ap}(\theta) = i_{as}(\theta)$. From the phase currents and the switches states, the output dc current i_{sDC} is given by:

for $0 \leq \theta \leq \varphi$

$$i_{sDC}(\theta) = 0 \quad (4.9)$$

for $\varphi \leq \theta \leq D$

$$i_{sDC}(\theta) = i_{ap}(\theta) = \frac{U_p}{3\omega L}(dD - D + 2\theta - 2d\theta + 2d\varphi) \quad (4.10)$$

for $D \leq \theta \leq \varphi + D$

$$i_{sDC}(\theta) = i_{ap}(\theta) = \frac{U_p}{3\omega L}(dD + D + 2d\varphi - 2d\theta) \quad (4.11)$$

for $\varphi + D \leq \theta \leq \frac{2\pi}{3}$

$$i_{sDC}(\theta) = 0 \quad (4.12)$$

As shown in Figure 4.1. The peak of the ac transformer current occurs at $\theta = D$:

$$i_{sDC, peak}(\theta) = i_{ap}(D) = \frac{U_p}{3\omega L}(D - dD + 2d\varphi) \quad (4.13)$$

This shows that the duty cycle of the switching signal is the effective parameter for regulating the peak value of the transformer phase currents at fault conditions. Using the state-space averaging technique, the average output DC current is obtained:

$$\overline{i_{sDC}}(t) = \frac{\varphi U_p}{2\pi\omega L} (2D - \varphi) \quad (4.14)$$

And the input-output voltage ratio is given by:

$$\frac{U_s}{U_p} = \frac{\varphi R_L}{2\pi\omega L} (2D - \varphi) \quad (4.15)$$

Finally, the average output power is calculated to be:

$$P = \frac{\varphi d U_p^2}{2\pi\omega L} (2D - \varphi) \quad (4.16)$$

Therefore, as described in Figure 4.2, the three-phase DAB will work using the SPS modulation at normal condition. However, once a fault is detected, the three-phase DAB will switch to be controlled using the VDCSPS approach. The VDCSPS control technique will constrain the peak AC current passing through the transformer by finding the corresponding duty cycle D using (4.13). Also, the output DC current will be controlled using the load angle φ .

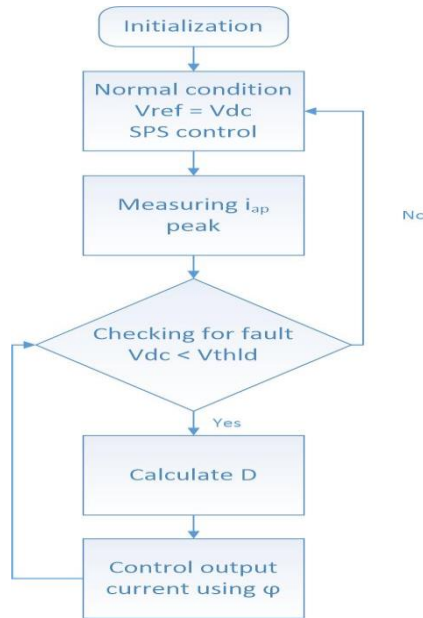


Figure 4.2 VDCSPS control flow chart

4.2 Modified Asymmetrical Duty Cycle Modulation for Fault Control

The aforementioned VDCSPS control method was suggested to operate the three-phase DAB converter at fault conditions. By varying the duty cycle of the modulation signal as an additional control parameter along with the load angle, VDCSPS method can control both the output DC current and the peak value of the AC transformer current. However, switches in this control technique suffer from hard turning off. Also, the maximum DC output current delivered in this mode is much lower than that of the normal condition which will affect the performance of the overcurrent protection scheme of the DC microgrid.

Therefore, a new method is proposed to overcome the drawbacks of the VDCSPS. This method is a modified version of the ADCC technique with different approach and derivation for it to be able to be utilized for fault ride-through operation. The operation principle and derivation of the modified asymmetrical duty cycle control (MADCC) approach is described in the following section.

4.2.1 Operation Principle

The MADCC is similar to the ADCC approach as the duty cycle of the primary bridge is different than that of the secondary bridge. In the ADCC, there are three control parameters which are the primary and secondary bridges duty cycles, D_p and D_s , as well as the load angle φ . However, the two duty cycles are dependent on each other, for example $D_p = dD_s$ in TCM-Buck which indicates that the system has only two independent control parameters. Also, this relation makes this approach unsuitable for very low voltage ratio conditions.

The proposed MADCC method aims to overcome the drawbacks and limitations of all discussed techniques for affective control of the three-phase DAB at fault conditions including the case of zero-voltage faults.

In this modulation approach, the duty cycle of the primary and secondary bridges, D_p and D_s , are different and independent of each other. This increases the number of control parameters and, hence, the controllability of the three-phase DAB converter at fault conditions. Figure 4.3 shows the switching states of the primary and secondary bridges, the AC voltage of both sides of the transformer, and the resulting AC current of the primary side of the transformer. The duty cycle of both the primary and secondary brides as well as the load angle are represented in terms of the phase position θ as:

$$D_p = \theta_2 \quad (4.17)$$

$$D_s = \theta_3 - \theta_1 \quad (4.18)$$

$$\varphi = \frac{1}{2}(\theta_3 + \theta_1 - \theta_2) \quad (4.19)$$

This current is a piecewise-linear phase current which can be derived for $0 \leq \theta \leq \theta_3$ by computing the voltage difference between the primary and secondary phase voltages as follows:

for $0 \leq \theta \leq \theta_1$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} (2 + d)\theta + i(0) \quad (4.20)$$

for $\theta_1 \leq \theta \leq \theta_3 - \frac{2\pi}{3}$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} (2 - d)(\theta - \theta_1) + i(\theta_1) \quad (4.21)$$

for $\theta_3 - \frac{2\pi}{3} \leq \theta \leq \theta_2$

$$i_{ap}(\theta) = \frac{2U_p}{3\omega L} (1 - d) \left(\theta - \theta_3 + \frac{2\pi}{3} \right) + i \left(\theta_3 - \frac{2\pi}{3} \right) \quad (4.22)$$

for $\theta_2 \leq \theta \leq \frac{2\pi}{3}$

$$i_{ap}(\theta) = -\frac{2dU_p}{3\omega L} (\theta - \theta_2) + i(\theta_2) \quad (4.23)$$

for $\frac{2\pi}{3} \leq \theta \leq \frac{2\pi}{3} + \theta_1$

$$i_{ap}(\theta) = -\frac{U_p}{3\omega L} (1 + 2d) \left(\theta - \frac{2\pi}{3} \right) + i \left(\frac{2\pi}{3} \right) \quad (4.24)$$

for $\frac{2\pi}{3} + \theta_1 \leq \theta \leq \theta_3$

$$i_{ap}(\theta) = -\frac{U_p}{3\omega L} (1 + d) \left(\theta - \frac{2\pi}{3} - \theta_1 \right) + i \left(\frac{2\pi}{3} + \theta_1 \right) \quad (4.25)$$

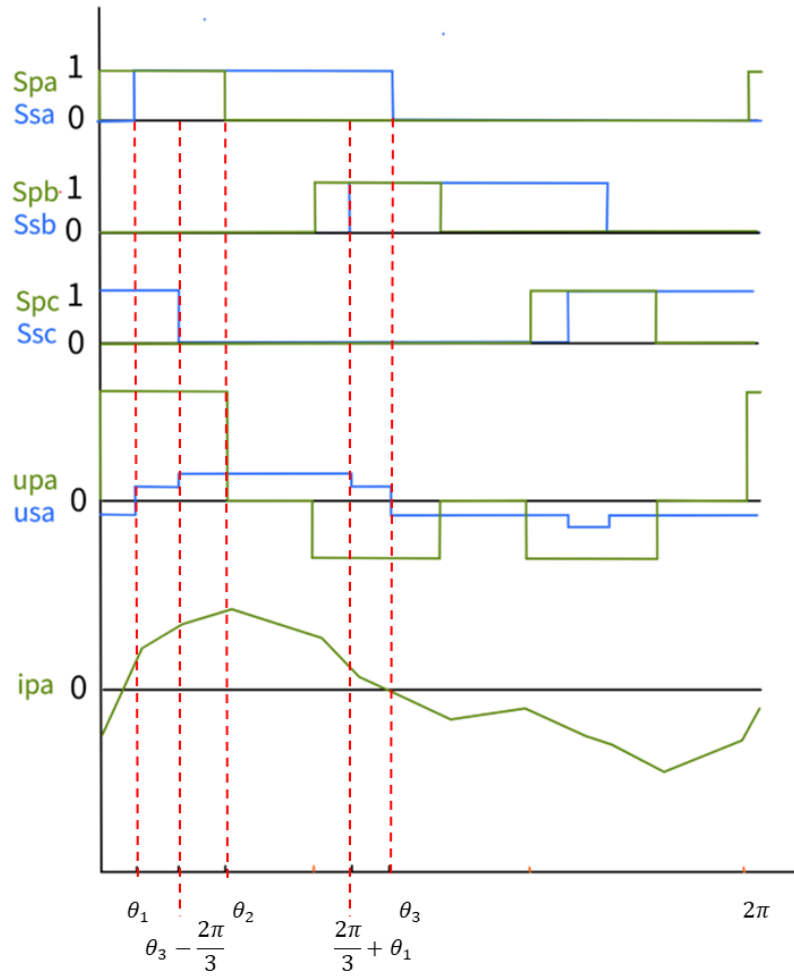


Figure 4.3 three-phase DAB converter switching states, AC voltages and primary AC current operating with the MADCC

By equating $i(0) = -i(\frac{2\pi}{3})$ we get:

$$i_{ap}(0) = \frac{U_p}{3\omega L} \left[-\theta_2 - d\theta_1 - \frac{1}{2}d\theta_3 + d\pi \right] \quad (4.26)$$

and after substituting $i_{ap}(0)$ in (4.20)-(4.25) we obtain:

for $0 \leq \theta \leq \theta_1$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} \left[(2 + d)\theta - \theta_2 - d\theta_1 - \frac{1}{2}d\theta_3 + d\pi \right] \quad (4.27)$$

for $\theta_1 \leq \theta \leq \theta_3 - \frac{2\pi}{3}$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} (2-d)\theta + d\theta_1 - \theta_2 - \frac{1}{2}d\theta_3 + d\pi \quad (4.28)$$

for $\theta_3 - \frac{2\pi}{3} \leq \theta \leq \theta_2$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} \left[2(1-d)\theta - \theta_2 + d\theta_1 + \frac{1}{2}d\theta_3 + d\frac{\pi}{3} \right] \quad (4.29)$$

for $\theta_2 \leq \theta \leq \frac{2\pi}{3}$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} \left[-2d\theta + \theta_2 + d\theta_1 + \frac{1}{2}d\theta_3 + d\frac{\pi}{3} \right] \quad (4.30)$$

for $\frac{2\pi}{3} \leq \theta \leq \frac{2\pi}{3} + \theta_1$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} \left[-(1+2d)\theta + \theta_2 + d\theta_1 + \frac{1}{2}d\theta_3 + \frac{2\pi}{3} + d\frac{\pi}{3} \right] \quad (4.31)$$

for $\frac{2\pi}{3} + \theta_1 \leq \theta \leq \theta_3$

$$i_{ap}(\theta) = \frac{U_p}{3\omega L} \left[-(1+d)\theta + \theta_2 + \frac{1}{2}d\theta_3 + \frac{2\pi}{3} - d\frac{\pi}{3} \right] \quad (4.32)$$

For Maximum output current and to realize ZCS in the secondary bridge:

$i(\theta_1) = i(\theta_3) = 0$, hence and after solving, we get:

$$2\theta_1 - \theta_2 - \frac{1}{2}d\theta_3 + d\pi = 0 \quad (4.33)$$

and

$$\theta_2 - \theta_3 + \frac{2\pi}{3} - \frac{1}{2}d\theta_3 + d\frac{\pi}{3} = 0 \quad (4.34)$$

The peak phase current can be represented by:

$$i_{sDC, peak}(\theta) = i_{ap}(\theta_2) = \frac{U_p}{3\omega L} \left[\theta_2 + d\theta_1 - 2d\theta_2 + \frac{1}{2}d\theta_3 + d\frac{\pi}{3} \right] \quad (4.35)$$

This shows that θ_2 or the duty cycle of the primary bridge $\theta_2 = D_p$ is the effective parameter for regulating the peak value of the transformer phase currents at fault

conditions. Using the state-space averaging technique, the average output DC current is obtained:

$$\begin{aligned} \overline{i_{sDC}}(t) = \frac{U_p}{2\pi\omega L} & \left(-\theta_1^2 - \theta_2^2 - \frac{1}{2}\theta_3^2 + \theta_1\theta_2 + \theta_2\theta_3 + \frac{2\pi}{3}\theta_3 - \frac{2\pi^2}{9} \right. \\ & \left. - \frac{1}{2}d\theta_3^2 - d\frac{\pi}{3}\theta_1 + d\frac{\pi}{3}\theta_3 + \frac{1}{2}d\theta_1\theta_3 \right) \end{aligned} \quad (4.36)$$

And the input-output voltage ratio is given by:

$$\begin{aligned} \frac{U_s}{U_p} = \frac{R_L}{2\pi\omega L} & \left(-\theta_1^2 - \theta_2^2 - \frac{1}{2}\theta_3^2 + \theta_1\theta_2 + \theta_2\theta_3 + \frac{2\pi}{3}\theta_3 - \frac{2\pi^2}{9} - \frac{1}{2}d\theta_3^2 \right. \\ & \left. - d\frac{\pi}{3}\theta_1 + d\frac{\pi}{3}\theta_3 + \frac{1}{2}d\theta_1\theta_3 \right) \end{aligned} \quad (4.37)$$

Finally, the average output power is derived to be:

$$\begin{aligned} P = \frac{d U_p^2}{2\pi\omega L} & \left(-\theta_1^2 - \theta_2^2 - \frac{1}{2}\theta_3^2 + \theta_1\theta_2 + \theta_2\theta_3 + \frac{2\pi}{3}\theta_3 - \frac{2\pi^2}{9} - \frac{1}{2}d\theta_3^2 \right. \\ & \left. - d\frac{\pi}{3}\theta_1 + d\frac{\pi}{3}\theta_3 + \frac{1}{2}d\theta_1\theta_3 \right) \end{aligned} \quad (4.38)$$

Therefore, as described in Figure 4.4, the three-phase DAB will work using the SPS modulation at normal condition. However, once a fault is detected, the three-phase DAB will switch to be controlled using the MADCC approach. The MADCC control technique will constrain the peak AC current passing through the transformer by finding the appropriate primary and secondary duty cycles. Also, the output DC current will be controlled using the load angle φ .

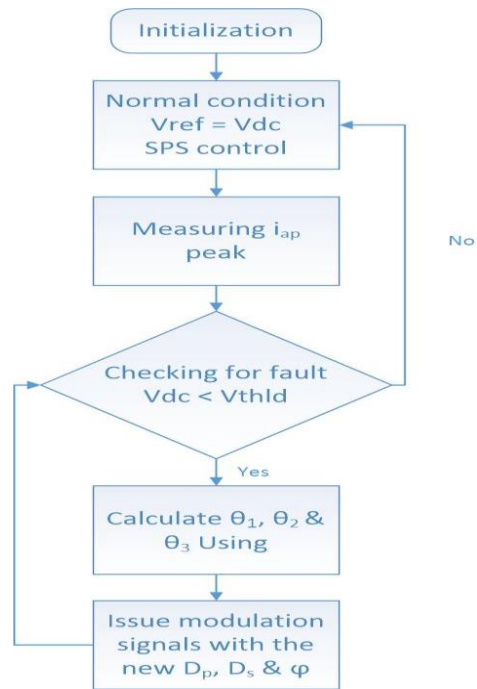


Figure 4.4 MADCC control flow chart

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Simulative Verification

Using MATLAB Simulink, the conventional and proposed modulation schemes are verified and evaluated. With the simulation parameters listed in Table 5.1, the three-phase DAB circuit was built and simulated at both normal and fault conditions. The input DC voltage U_p is constant throughout the simulated research, whereas the output DC voltage U_s controlled in normal conditions to be equal to U_p and changeable in fault conditions depending on the fault resistance.

Table 5.1: Simulation Parameters of the three-phase DAB Converter

Parameter	Value
Primary DC voltage U_p	30 V
Secondary DC voltage U_s	30 V
Output dc-link capacitance C_s	470 μF
Switching frequency f	20 kHz
Transformer turns ration N	1:1
Primary leakage inductance L_p	125 μH
Secondary leakage inductance L_s	125 μH

5.1.1 Single Phase shift

In this thesis, the three-phase DAB will run with SPS at normal conditions due to its many advantages including the high-power transferring capability. Also, the three-phase DAB will be simulated with SPS at fault conditions for comparison purposes with the proposed control methods. Therefore, the behavior of the three-phase DAB controlled using the conventional SPS method is firstly validated in this section,.

a. At normal conditions

Once the simulation started, the SPS control will track the reference voltage, which is set to be 30 V in this case, and the DC-link capacitor will be gradually charged. Figure 5.1 shows control scheme performance by displaying the output DC voltage and current after starting the simulation. Furthermore, the steady state operation of the three-phase DAB is illustrated in Figure 5.2 with the primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{SDC} . Finally, the load angle φ behaviour for voltage tracking is described in Figure 5.3.

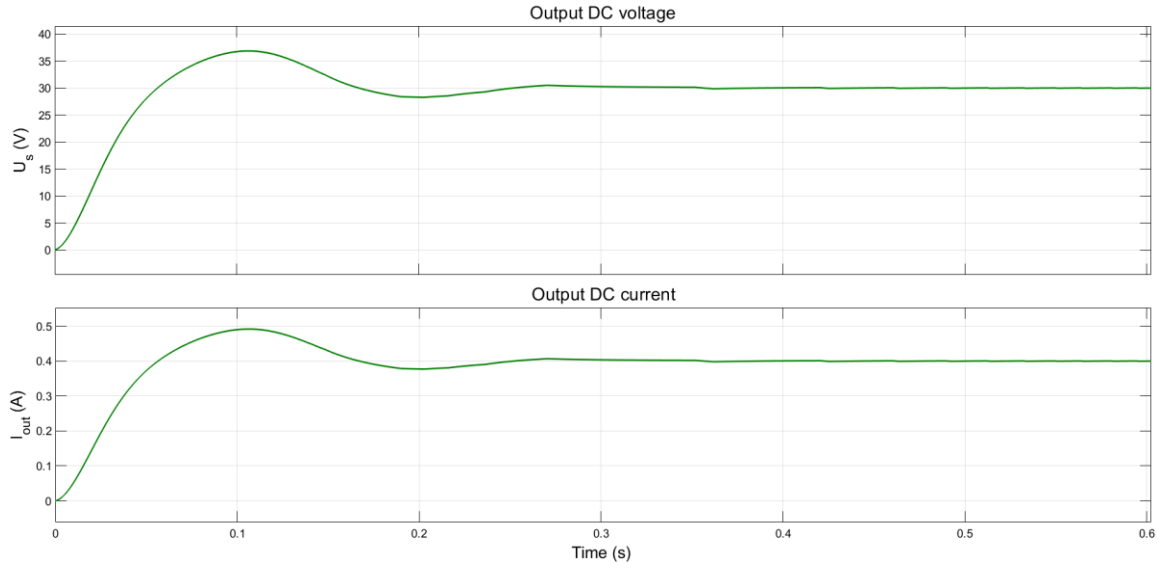


Figure 5.1 SPS DC output voltage and current U_s & I_{out} at normal condition

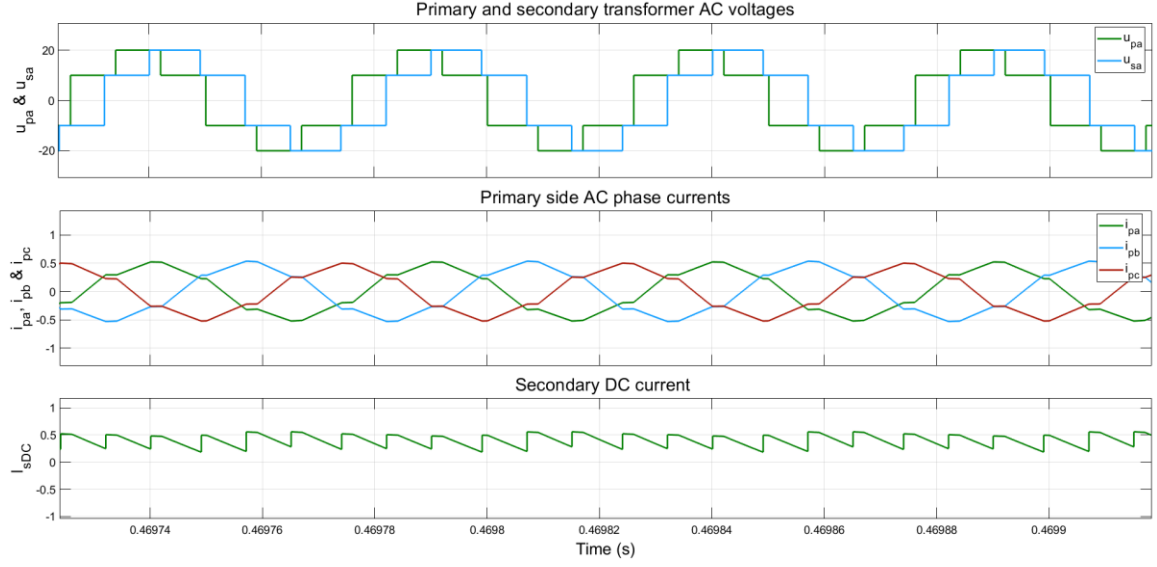


Figure 5.2 SPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current i_{sdc} at normal conditions

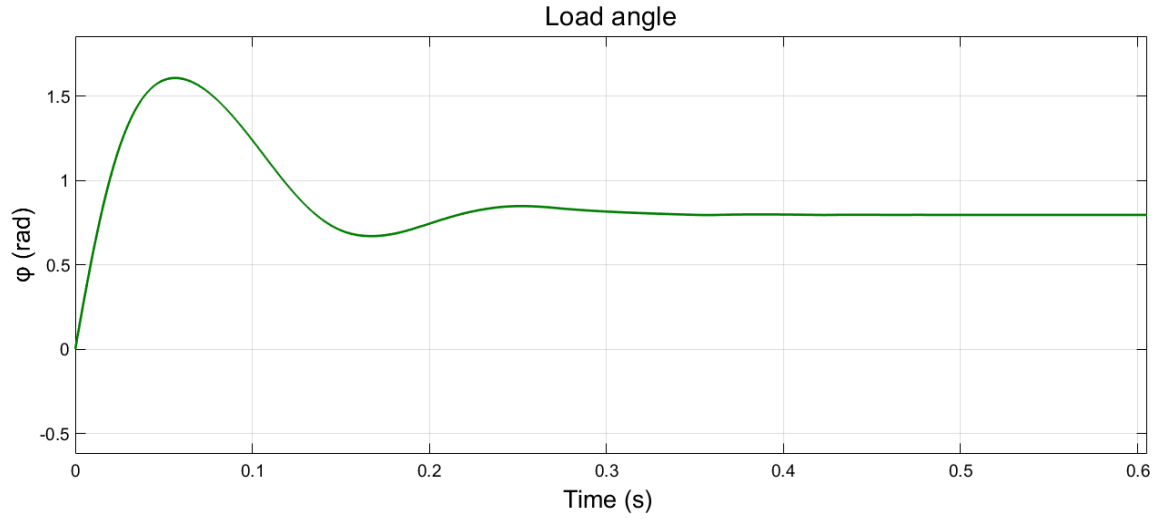


Figure 5.3 SPS load angle φ at normal conditions

b. At fault condition

The performance of SPS control was also simulated under fault conditions. A short circuit fault was applied across the terminals of the DC-link capacitor at 0.61s time instant. In this case, SPS control scheme is controlling the DC output current to a reference value of 0.4 A as in the normal situation. Figure 5.4 shows the fault instance and its impact on the output DC voltage and current.

Figure 5.5 shows the transformer AC primary and secondary voltages in that the secondary AC voltage collapsed to zero volt. Also, the AC three phase currents of the primary side

are presented in the same figure. We can see the increase in the peak value of the current from $i_{pa,peak} = 0.5 \text{ A}$ to $i_{pa,peak,F} = 0.67 \text{ A}$ which is one of the drawbacks of the SPS method when dealing with faults. Finally, the waveform of the secondary DC current I_{sDC} is also illustrated in F.g. 18. The fault incident also affected the load angle value as described in Figure 5.6.

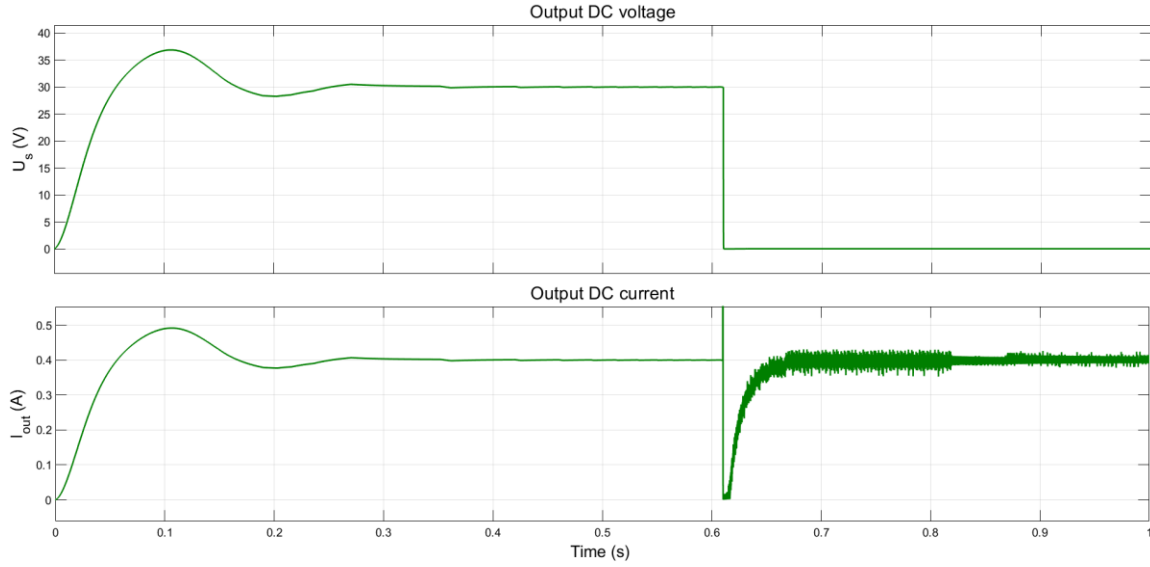


Figure 5.4 SPS DC output voltage and current U_s & I_{out} at fault condition

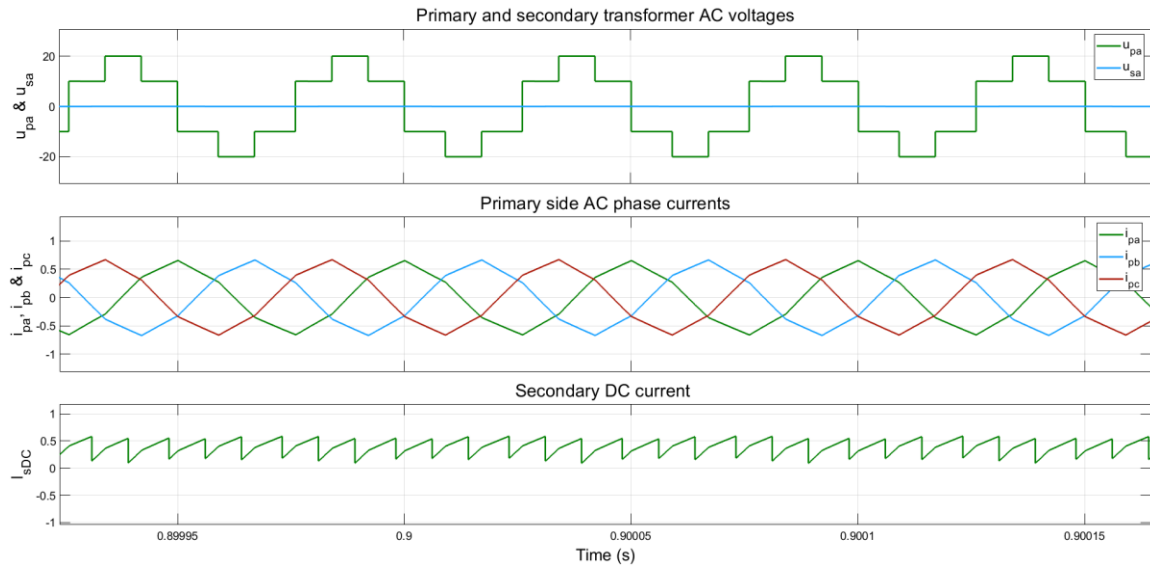


Figure 5.5 SPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at fault conditions

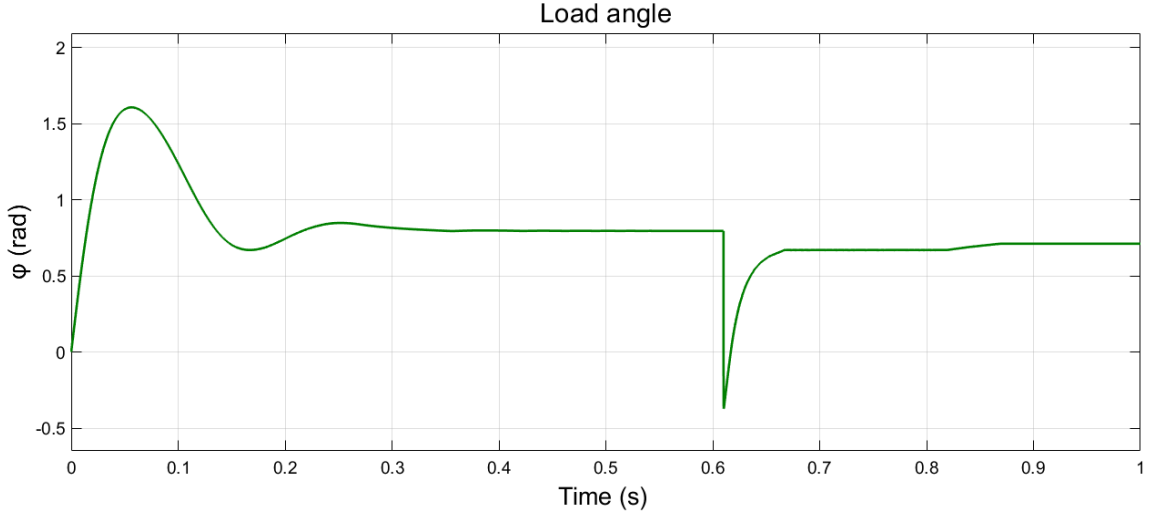


Figure 5.6 SPS load angle φ at fault conditions

5.1.2 Variable Duty Cycle Single Phase Shift Modulation

For the proposed control method to be verified and examined, VDCSPS control method was applied to the three-phase DAB simulated circuit after the occurrence of fault. The system will run with SPS at normal conditions and switch to VDCSPS at the instant of fault incident.

a. Case 1: zero voltage ratio fault

VDCSPS starts by setting the required peak value of the transformer AC current $i_{pa, peak}$ Which is determined from its value at normal condition, i.e. $i_{pa, peak} = 0.5 A$ in this simulation case. Using (4.13), the calculated duty cycle is almost 25% and by controlling the load angle φ the maximum output DC current is almost 0.3 A.

Figure 5.7 shows the behaviour of the three-phase DAB converter after having a short circuit fault at $t = 0.61s$ by displaying the output DC voltage and current. Figure 5.8 shows the transformer AC primary and secondary voltages in that the secondary AC voltage collapsed to zero volt. Also, the AC three phase currents of the primary side are presented in the same figure. We can see the peak value of the current is regulated to the predefined value, i.e. $i_{pa, peak, F} = 0.5 A$. Finally, the waveform of the secondary DC current I_{sDC} is also illustrated in Figure 5.8. The fault incident also affected the load angle value as described in Figure 5.9.

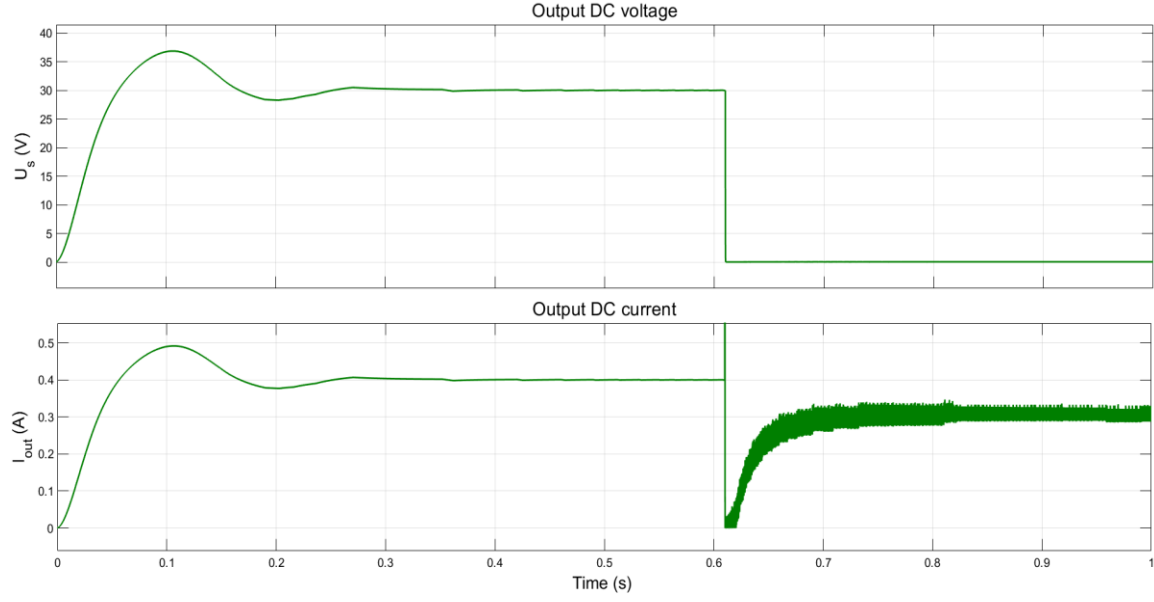


Figure 5.7 VDCSPS DC output voltage and current U_s & I_{out} at zero-voltage fault

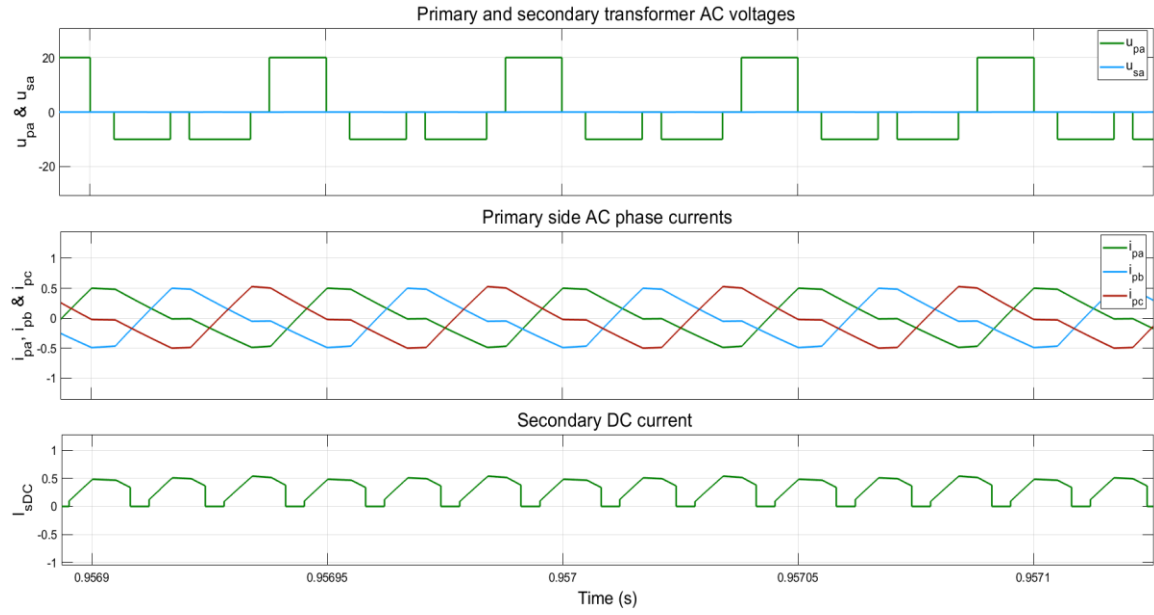


Figure 5.8 VDCSPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at zero-voltage fault

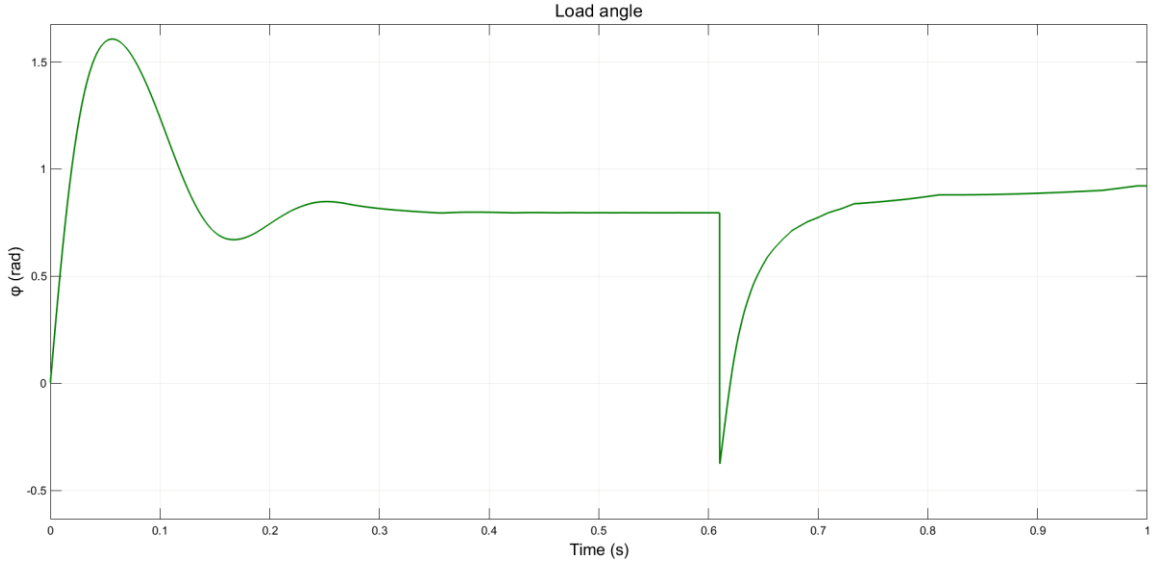


Figure 5.9 VDCSPS load angle ϕ at zero-voltage fault

b. Case 2: 0.1 voltage ratio fault

To validate the reliability of the VDCSPS, an additional case with a non- bolted fault was also simulated. The same above simulation case was repeated but with a fault causing a voltage ratio of 0.1. This small voltage ratio did not cause a significant impact on the control parameters as shown in the following results. The calculated duty cycle of this case is 25.5%, and the output DC current could reach to 0.32 A by controlling the load angle ϕ .

The response of the three-phase DAB converter after having this fault at $t = 0.61s$ is shown in Figure 5.10 by displaying the output DC voltage and current. Figure 5.11 shows the transformer AC primary and secondary voltages in that the secondary AC voltage collapsed to 3 V. Also, the AC three phase currents of the primary side are presented in the same figure. We can see the peak value of the current is regulated to the predefined value, i.e. $i_{pa,peak,F} = 0.5 A$. Finally, the waveform of the secondary DC current I_{SDC} is also illustrated in the same figure. The fault incident also affected the load angle value as described in Figure 5.12.

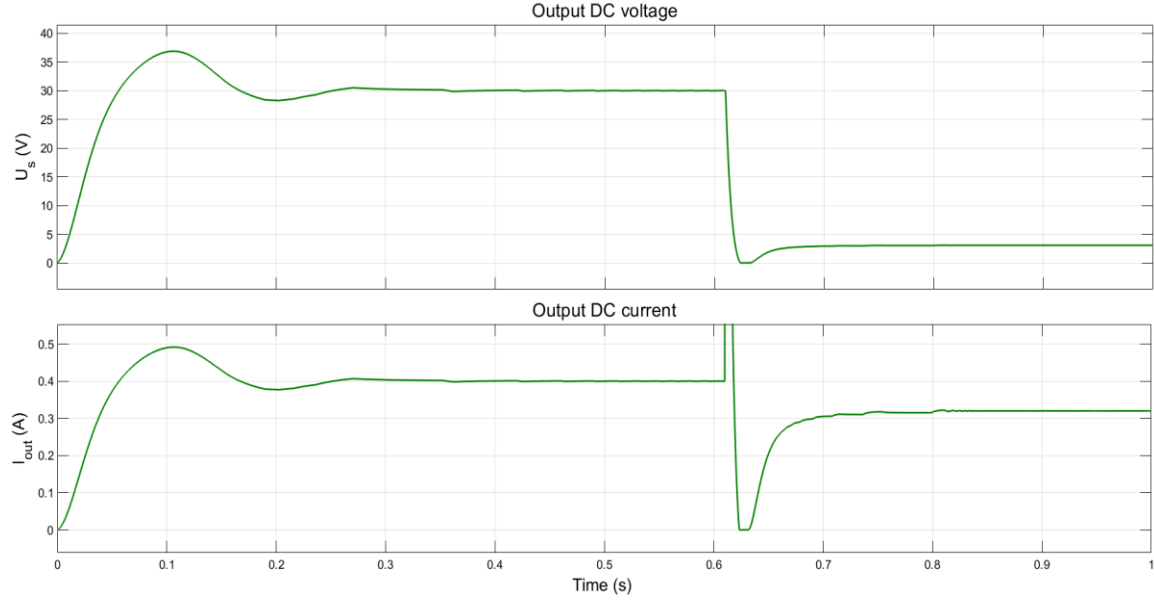


Figure 5.10 VDCSPS DC output voltage and current U_s & I_{out} at 0.1 voltage ratio fault

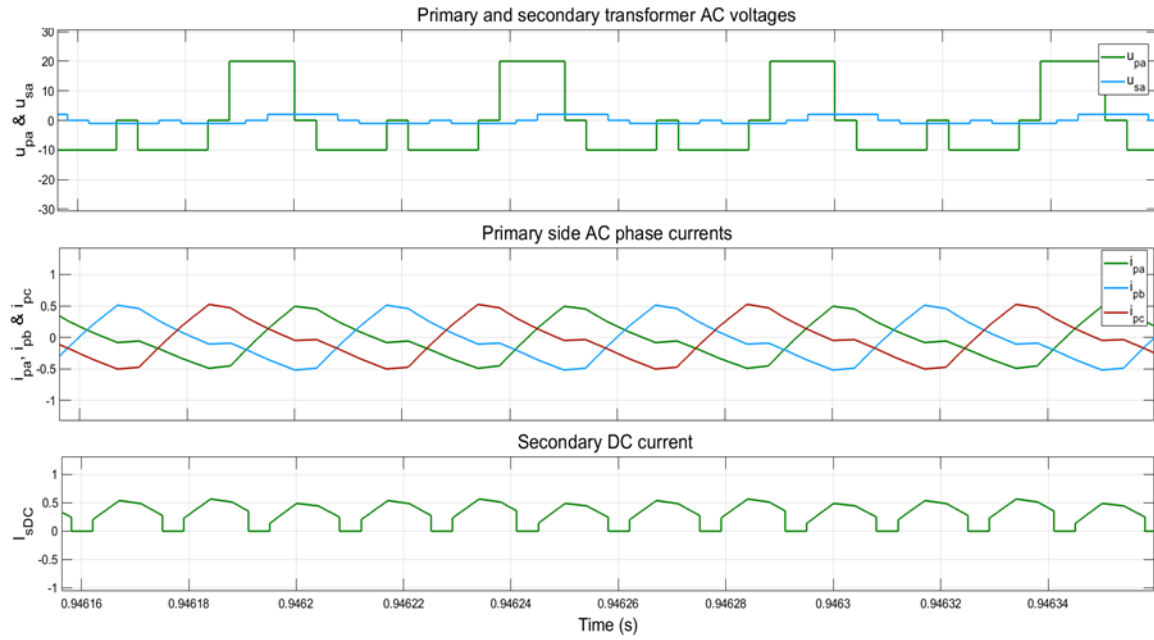


Figure 5.11 VDCSPS primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current I_{sDC} at 0.1 voltage ratio fault

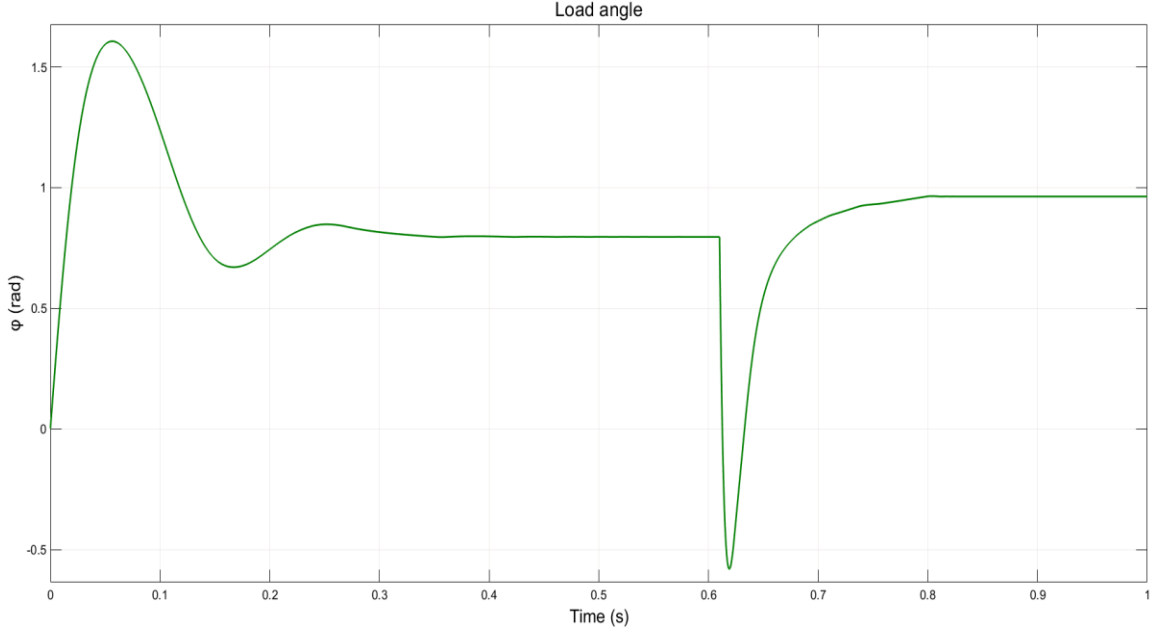


Figure 5.12 VDCSPS load angle ϕ at 0.1 voltage ratio fault

5.1.3 Modified Asymmetrical Duty Cycle Modulation for Fault Control

In this thesis, the proposed MADCC is also verified and examined via MATLAB Simulink circuit simulator. In this simulation test, the three-phase DAB circuit is originally controlled using the conventional SPS modulation at normal situations. Then, at the moment of voltage collapse caused by the fault incident, the MADCC control will take charge to regulate the three-phase DAB currents.

In normal conditions, the value of AC transformer peak current $i_{sDC, peak}$ will be stored and used as a reference value for the MADCC to find the suitable control parameters. D_p , D_s , ϕ are obtained using (4.33), (4.34), and (4.35) to insure proper control of the peak current value, maximum output current, and soft-switching operation.

a. Case 1: zero voltage ratio fault

In this simulation case, the control parameters are calculated using the system parameters and the MADCC equations. the used duty cycles of the primary and secondary bridges are $D_p = 25\%$ & $D_s = 45.8\%$, while the load angle ϕ is determined to be equal to 1.42 rad in this case study.

The behaviour of the three-phase DAB converters controlled using MADCC in fault conditions is illustrated in Figure 5.13 by displaying the output DC voltage and current following a short circuit fault occurs at $t = 0.61\text{s}$. It can be seen that the output DC current I_{sDC} is almost 0.4 A which is the same current value as in the normal condition. The transformer AC primary and secondary voltages are shown in Figure 5.14, where the

secondary AC voltage has fallen to zero volt. The primary side AC three phase currents are also shown in the same figure. We can observe that the current's peak value is restricted to a predetermined value, $i_{pa,peak,F} = 0.5 \text{ A}$. Finally, and in the same figure, the waveform of the secondary DC current I_{SDC} is also presented.

Soft switching operation of the three-phase DAB converter modulated using MADCC technique is also verified in this study. In the secondary bridge, all switches turn on with zero-voltage switching (ZVS) and zero-current switching (ZCS) and they also realize ZCS turn off. Figure 5.15, verifies the soft switching operation of the secondary bridge by showing the waveform of the AC phase voltage and current of the secondary side of the transformer. Although, all switches in the primary bridge also turn on with ZVS, they suffer from hard turn off operation.

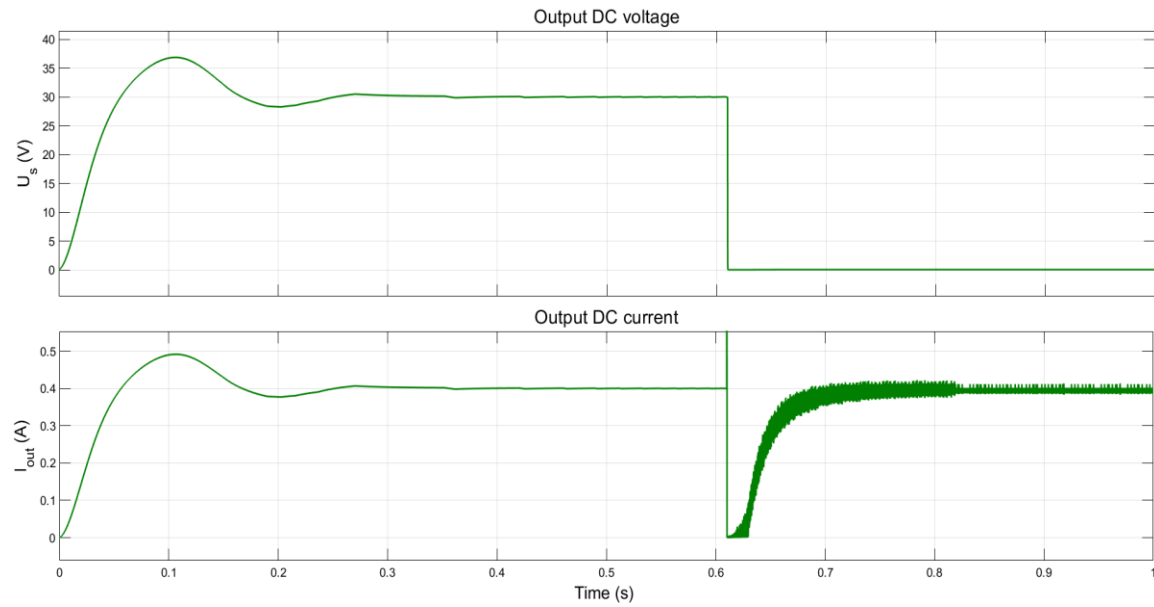


Figure 5.13 MADCC DC output voltage and current U_s & I_{out}

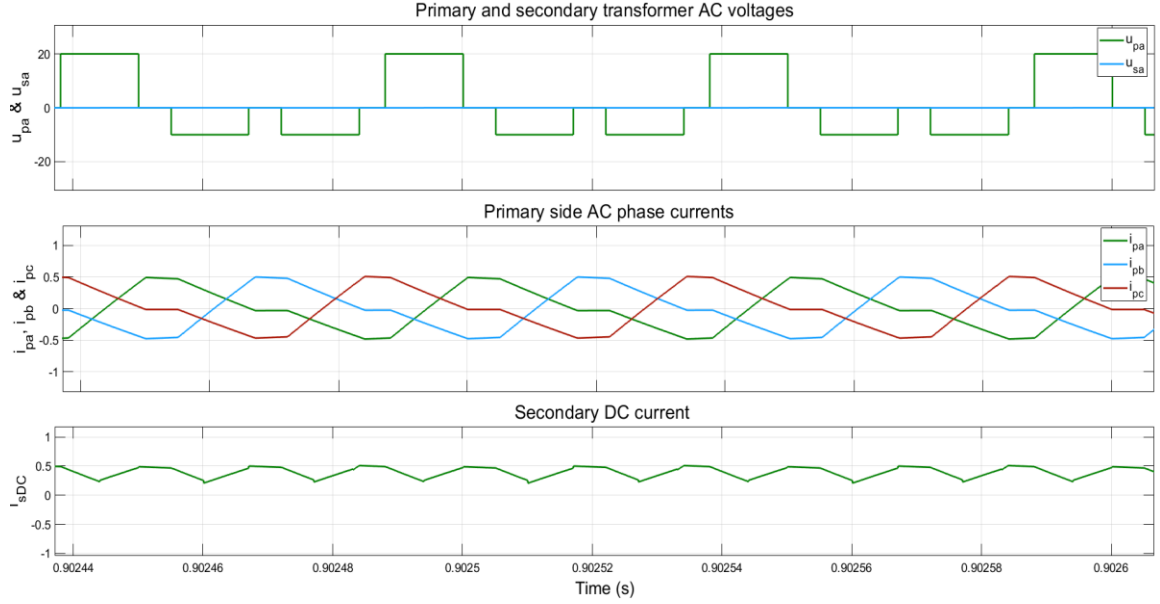


Figure 5.14 MADCC primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current i_{sDC}

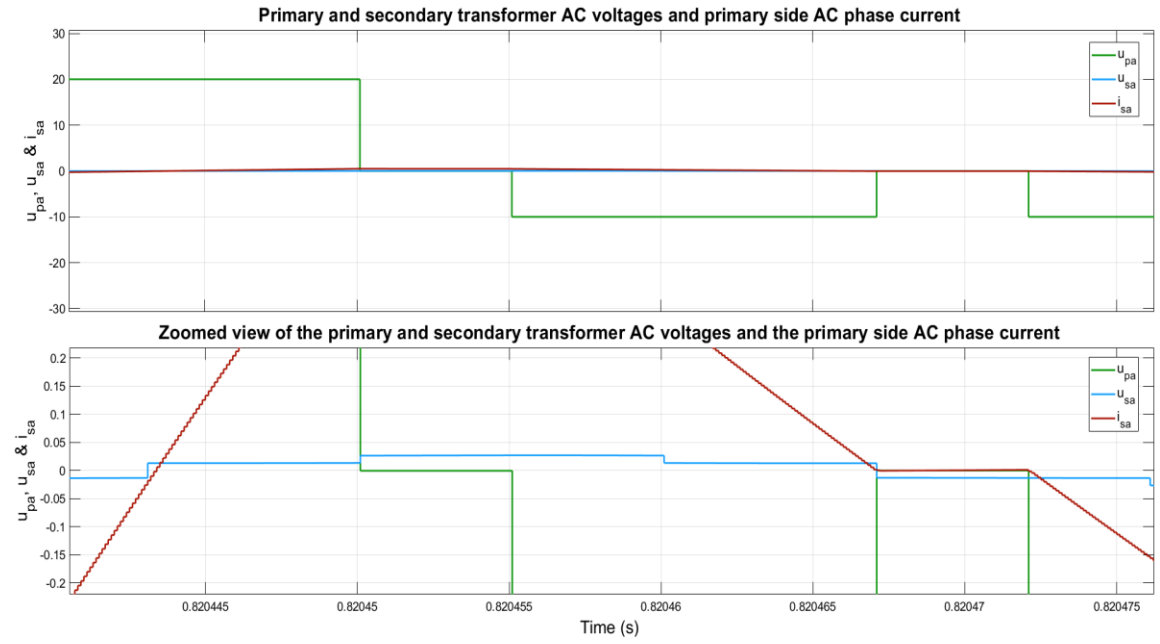


Figure 5.15 regular and zoomed view of the primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase current i_{pa} for soft switching verification

b. Case 2: 0.1 voltage ratio fault

Just like VDCSPS variation approach, another case is conducted to test the MADCC performance when having non-bolted faults. The same above simulation case was repeated but with a fault causing a voltage ratio of 0.1. This small voltage ratio did not cause a significant change on the control parameters as shown in the following results. The used duty cycles of the primary and secondary bridges are $D_p = 24.5\%$ & $D_s = 45.4\%$, while the load angle φ is determined to be equal to 1.3 rad in this case study.. The behaviour of the three-phase DAB converters controlled using MADCC in fault conditions is illustrated in Figure 5.16 by displaying the output DC voltage and current following a short circuit fault occurs at $t = 0.61s$. It can be seen that the output DC current I_{sDC} is almost 0.4 A which is the same current value as in the normal condition. The transformer AC primary and secondary voltages are shown in Figure 5.17, where the secondary AC voltage has fallen to 3 V which is 10% of the primary voltage. The primary side AC three phase currents are also shown in the same diagram. We can observe that the current's peak value is restricted to a predetermined value, $i_{pa,peak,F} = 0.5$ A. Finally, and in the same figure, the waveform of the secondary DC current I_{sDC} is also presented.

Soft switching operation of the three-phase DAB converter modulated using MADCC technique is also verified in this case study. In the secondary bridge, all switches turn on with zero-voltage switching (ZVS) and zero-current switching (ZCS) and they also realize ZCS turn off. Figure 5.18 verifies the soft switching operation of the secondary bridge by showing the waveform of the AC phase voltage and current of the secondary side of the transformer. Although, all switches in the primary bride also turn on with ZVS, they suffer from hard turn off operation.

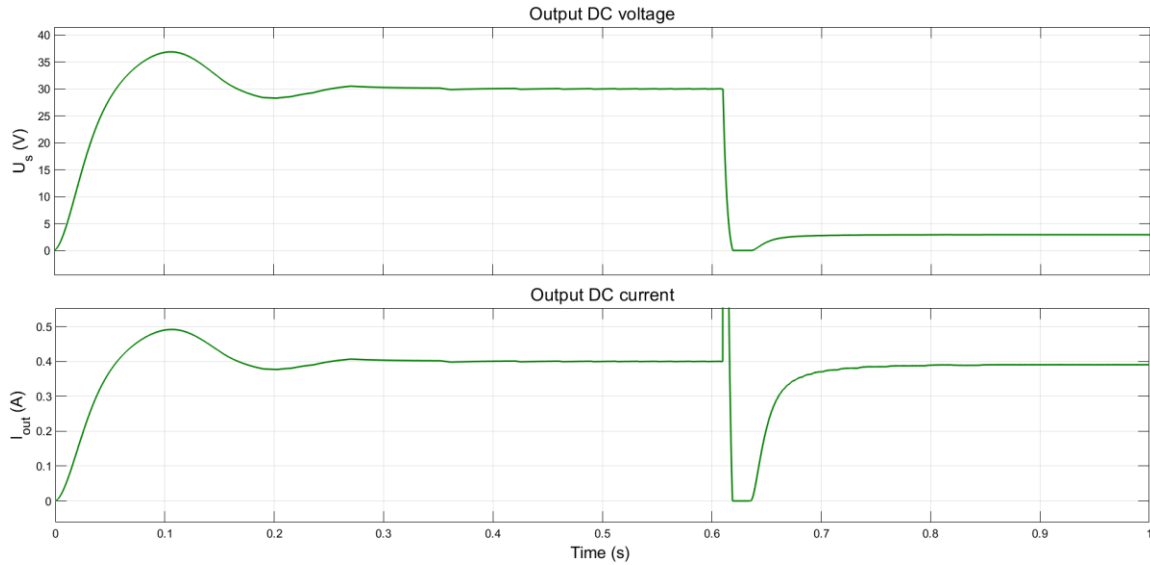


Figure 5.16 MADCC DC output voltage and current U_s & I_{out} at 0.1 voltage ratio fault

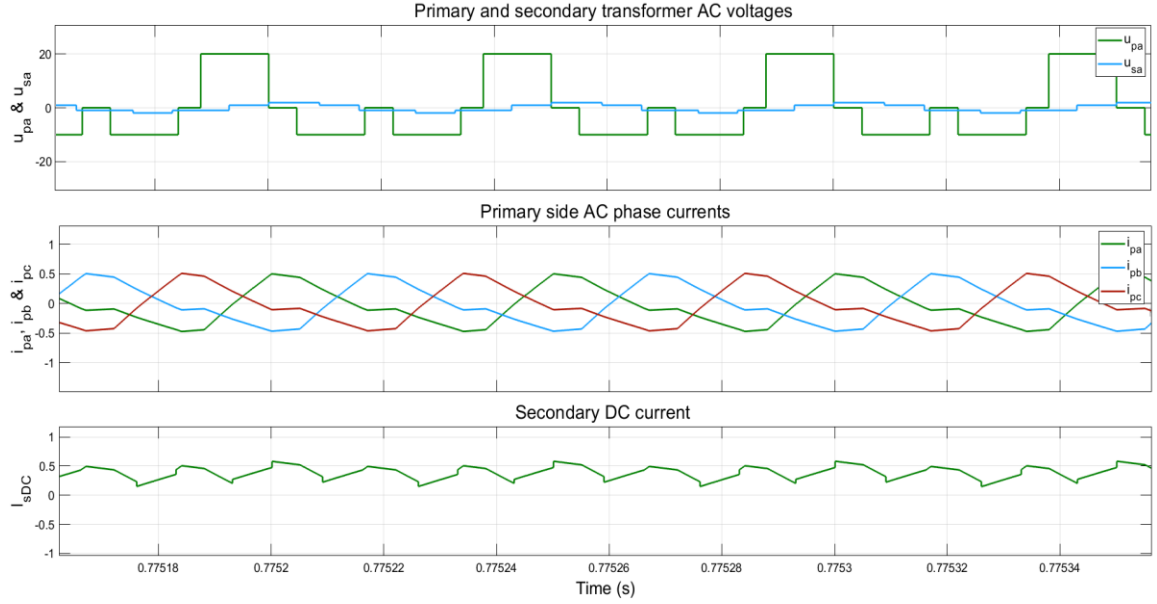


Figure 5.17 MADCC primary and secondary transformer AC voltages u_{pa} & u_{sa} , primary side AC phase currents i_{pa} , i_{pb} & i_{pc} , and the secondary DC current i_{sDC} at 0.1 voltage ratio fault

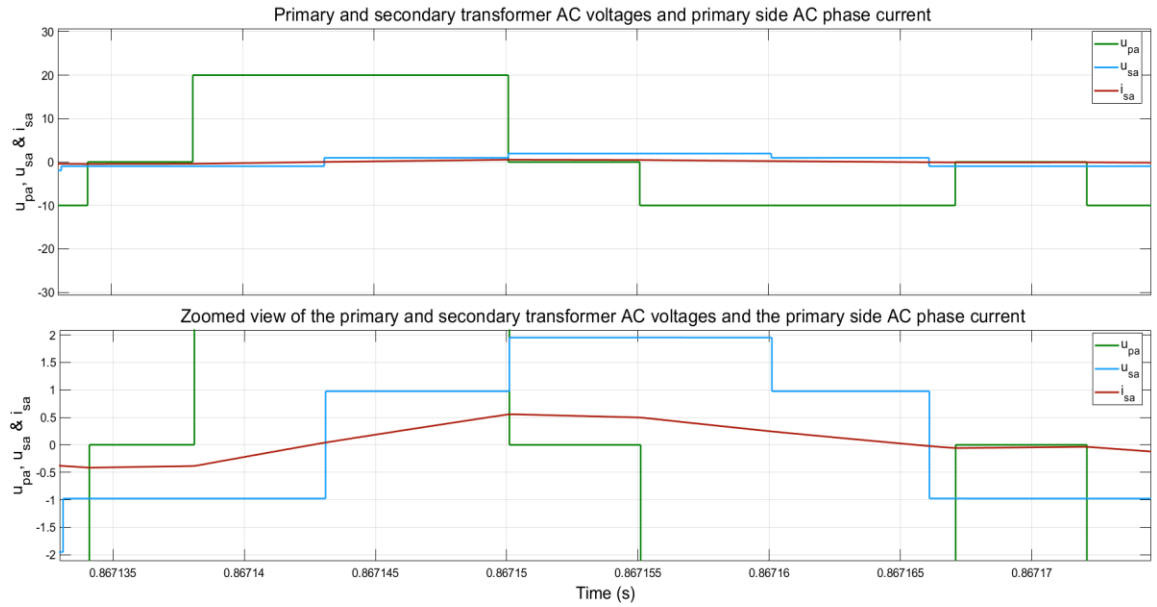


Figure 5.18 regular and zoomed view of the primary and secondary transformer AC voltages u_{pa} & u_{sa} , and primary side AC phase current i_{pa} for soft switching verification at 0.1 voltage ratio fault

5.2 Experimental Verification

The conventional SPS as well as the suggested VDCSPS and MADCC approaches has been developed and validated on a down-scaled laboratory prototype of the three-phase DAB converter. The experimental setup consists of the following devices:

- **DC source**
Figure 5.19 shows the used DC power supply. It provides constant voltage in the power class of up to 1,0 kW. The output voltage range is 40- 250 V while the current is from 0 to 10 A [101].
- **Two three-phase power converters**
The used three-phase power converters are provided by Taraz technologies inside a power electronics Rapid Development system (PELAB) as shown in Figure 5.20. This PELAB has two three-phase converters, used for the primary and secondary sides of the three-phase DAB, with Silicon carbide (SiC) MOSFETs as switching devices. The PELAB comes also with voltage and current measurement options fixed to some nodes and paths in the system [102].
- **Three-phase transformer**
The required medium-frequency transformer was designed, contracted, and wired manually in the lab as shown in Figure 5.21. It consists of three single-phase transformers constructed using E65/32/27 N27 ferrite cores and wired using 0.65 mm , 22 AWG, enameled wire with maximum current capacity of 0.92 A [103]. The transformer number of turns was determined using the following equation:
$$N = \frac{V}{k_f f A_e B_m} \quad (5.1)$$
Where V is the transformer input voltage, k_f is the waveform factor, which is 4 for square waves, A_e is the transformer effective cross-sectional area which is 535 mm^2 , and B_m is the flux density which is 0.05 T. The resulting number of turns is 14 turns in each side of the transformer.
- **Resistive load**
Figure 5.22 shows the used DC load which is a Three synchronously adjustable circular rheostats (step winding) with scale of (100 - 0%), each with a series resistor and fuse in the sliding-contact connection. The resistors are suitable for parallel, series, star and delta connections [104]. The used resistance in this experimental testing at normal conditions is 75Ω
- **Current sensor**
Since the PELAB cannot measure the output DC current, an external current sensor is implemented. As shown in Figure 5.23, the used current sensor is an SCK3 Series Hall-Effect Open Loop Current Sensor which can measure up to 50 A currents [105].

- dSPACE controller

The converter is controlled by dSPACE DS1103 PPC Controller Board which is designed to meet the requirements of modern rapid control prototyping as shown in Figure 5.24. This dSPACE reads measurements, process the control algorithm, and issue the modulation signals. Also, dSPACE was implemented for monitoring and measurements recording purposes.

The whole and connected experimental setup of the three-phase DAB circuit is shown in Figure 5.25.

The primary voltage of the three-phase DAB is chosen to be 30 V for safety purposes when dealing with faults as well as following some of the experimental testing circuits in the literature. Since we are testing the isolation ability of the three-phase DAB and its fault behavior, the transformer turns ratio was selected to be 1:1. However, the conventional and the proposed schemes are feasible for any transformer turns ratio. Also, and for simplicity, the voltage ratio d is controlled to be one, by controlling the secondary voltage to be 30 V. Based on the available capacitors in the lab, the used output capacitance is 470 μF . The prototype's specifications and experimental parameters are summarized in Table 5.2.

Different experimental tests were carried out for verification and examination of the proposed control methods of the three-phase converter. The performance of the SPS control approach was validated at both normal and fault conditions. At faulty situations, the proposed VDCSPS and MADCC approaches were also validated and compared to the SPS results.



Figure 5.19 DC Power supply



Figure 5.20 PE lab power converters

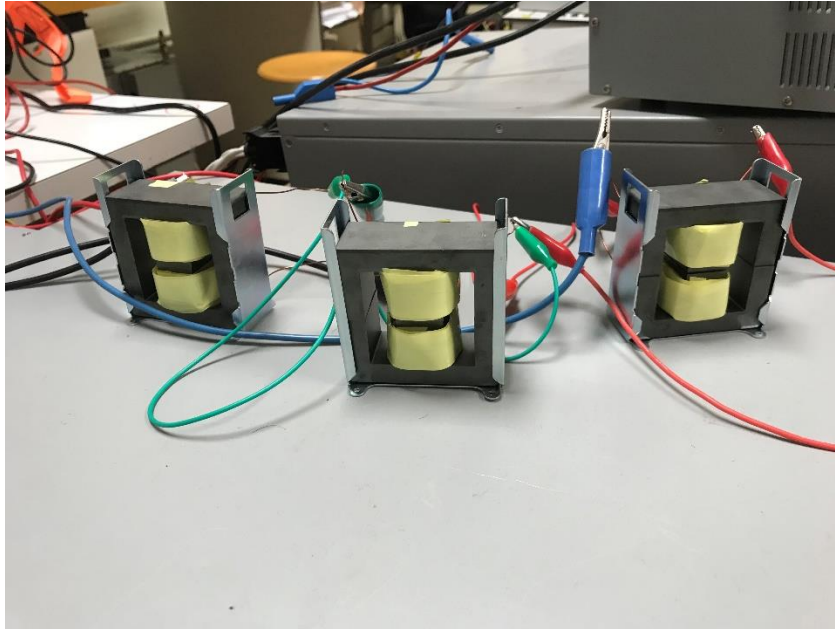


Figure 5.21 Three phase transformer

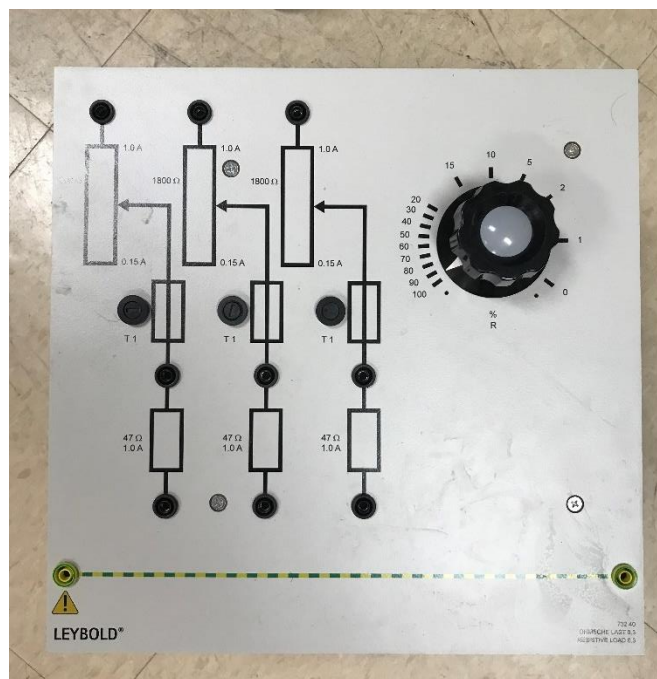


Figure 5.22 Resistive load

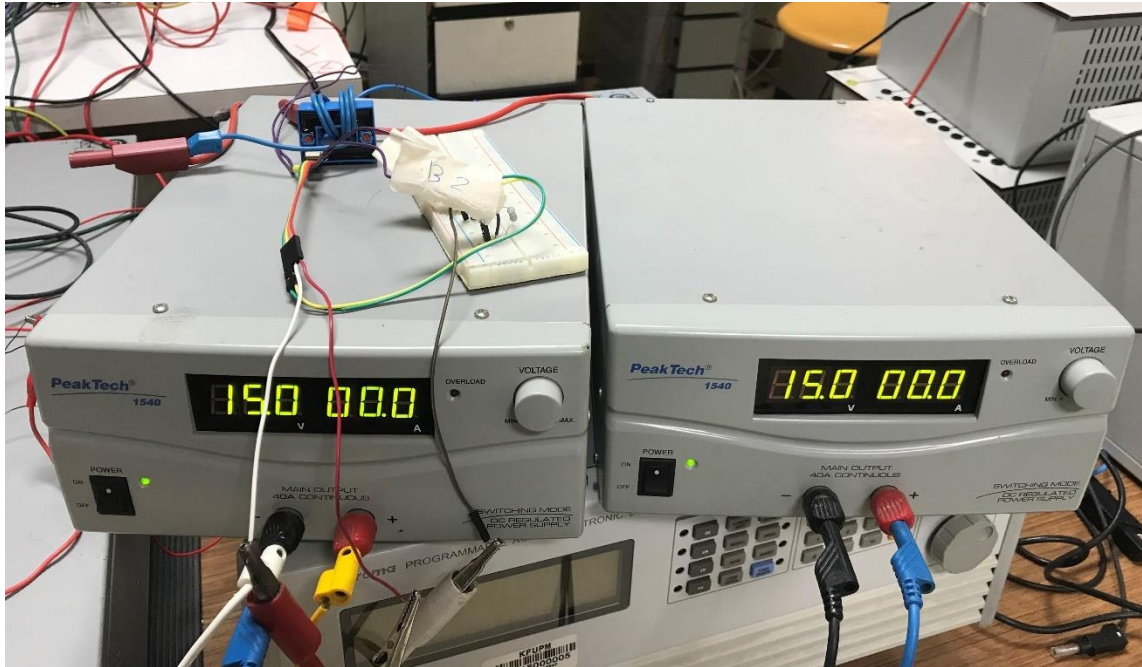


Figure 5.23 Current sensor

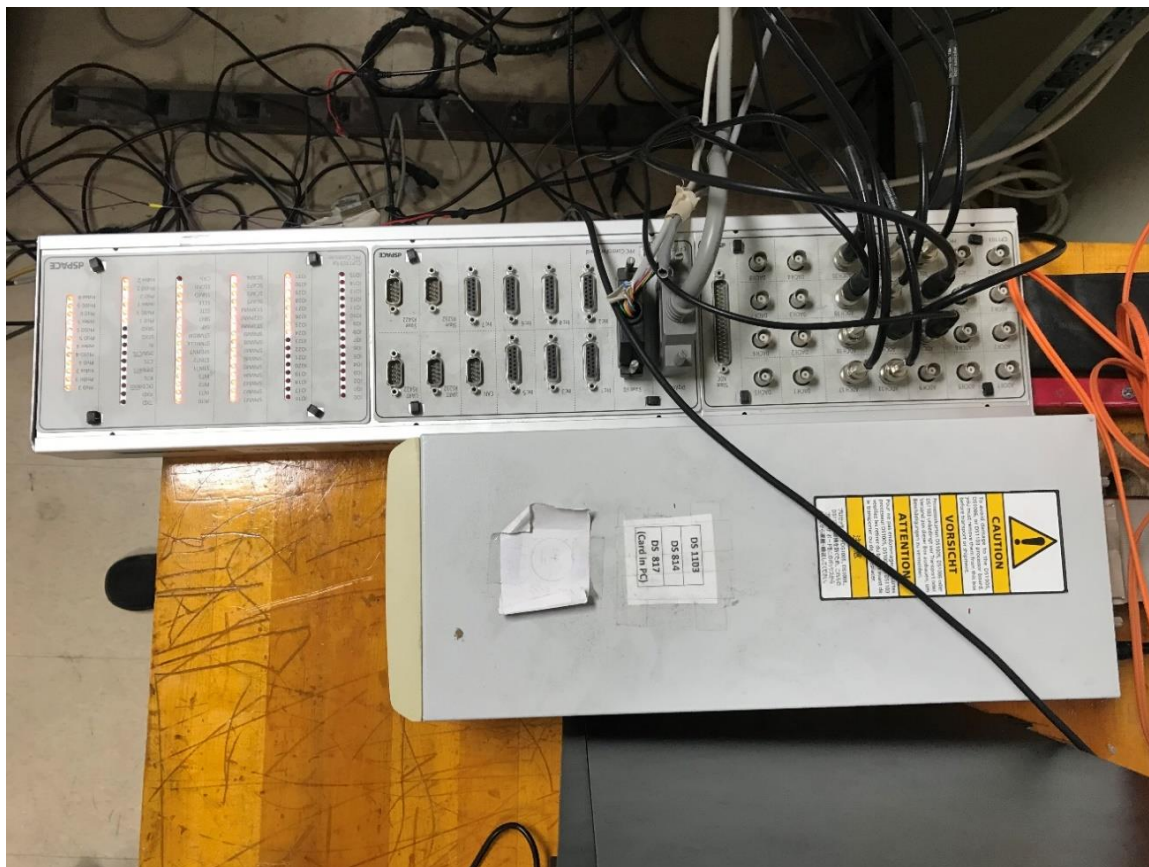


Figure 5.24 dSPACE DS1103 PPC Controller Board

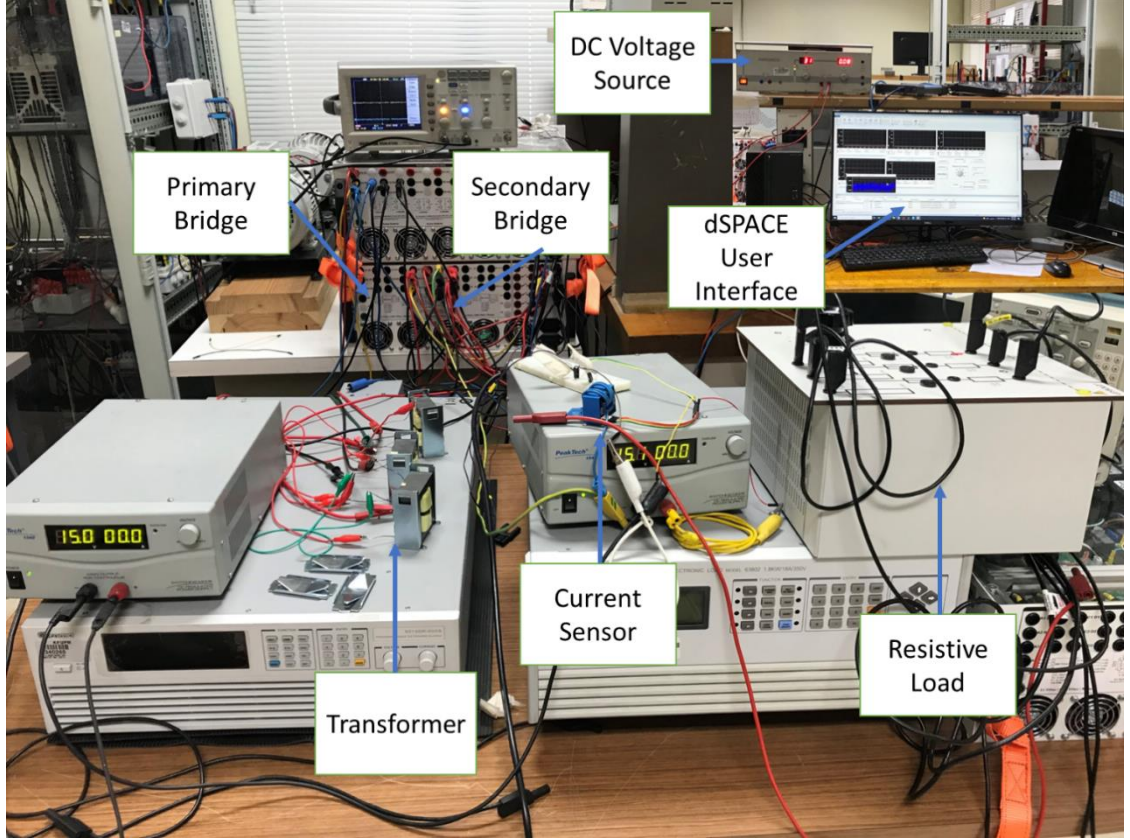


Figure 5.25 Three-phase DAB circuit experimental setup

Table 5.2: Experimental Parameters of the three-phase DAB Converter

Parameter	Value
Primary DC voltage U_p	30 V
Secondary DC voltage U_s	30 V
Output dc-link capacitance C_s	470 μF
Switching frequency f	20 kHz
Transformer turns ration N	1:1
Transformer leakage inductance L_σ	250 μH

5.2.1 Single Phase shift

The first conducted experimental test was to run the three-phase DAB using the SPS control method and validate its theoretical and simulation performance. Similar to the simulative test, the three-phase DAB with SPS modulation will be firstly tested at normal conditions then a fault will be applied for validation and comparison purposes.

a. At normal condition

Normal operation of the three-phase DAB was conducted using the SPS modulation. The reference voltage was set to be 30 V. the first measurement is taken for the primary and secondary transformer AC voltages u_{pa} & u_{sa} as illustrated in Figure 5.26 which shows the phase shift between the two sides of the three-phase DAB. Also, primary side AC phase current i_{pa} was measured and presented in Figure 5.27. It can be seen that the obtained results of both the AC primary voltages and current are similar to the simulation results with some range of inaccuracy caused by the used measurement devices.

The SPS control method was also tested by changing the reference voltage and check its voltage tracking ability. The reference voltage has been changed to various values which are 20 V, 15 V, 20 V, 40 V and 70 V and the measured output voltage was tracking these applied changes as shown in Figure 5.28.

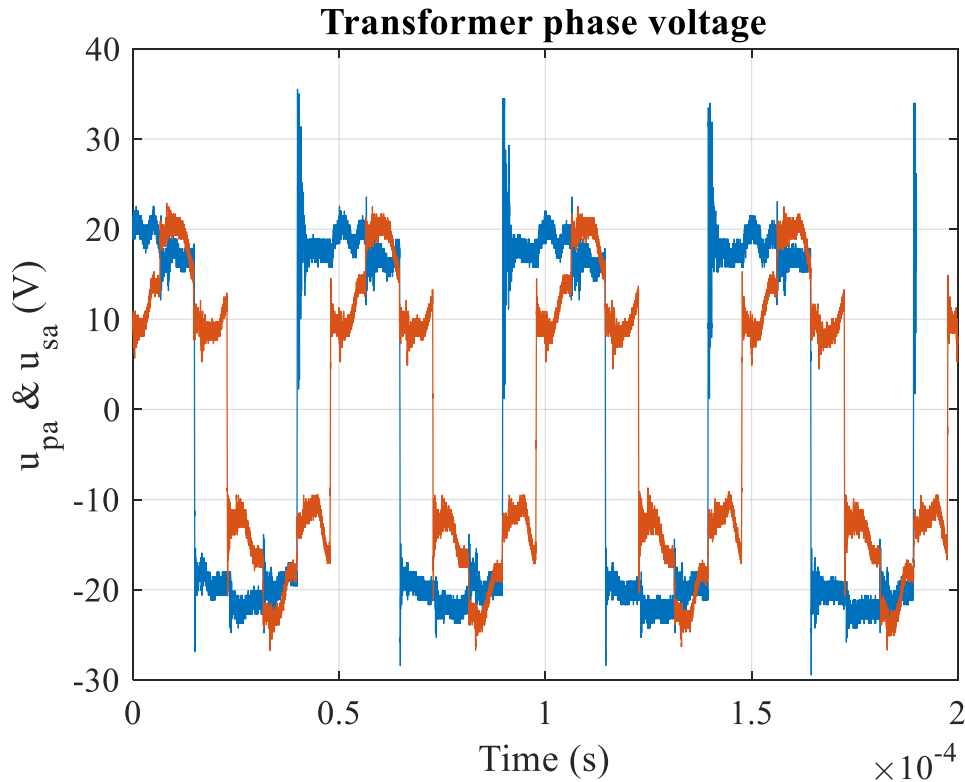


Figure 5.26 SPS primary and secondary transformer AC voltages u_{pa} & u_{sa} at normal condition

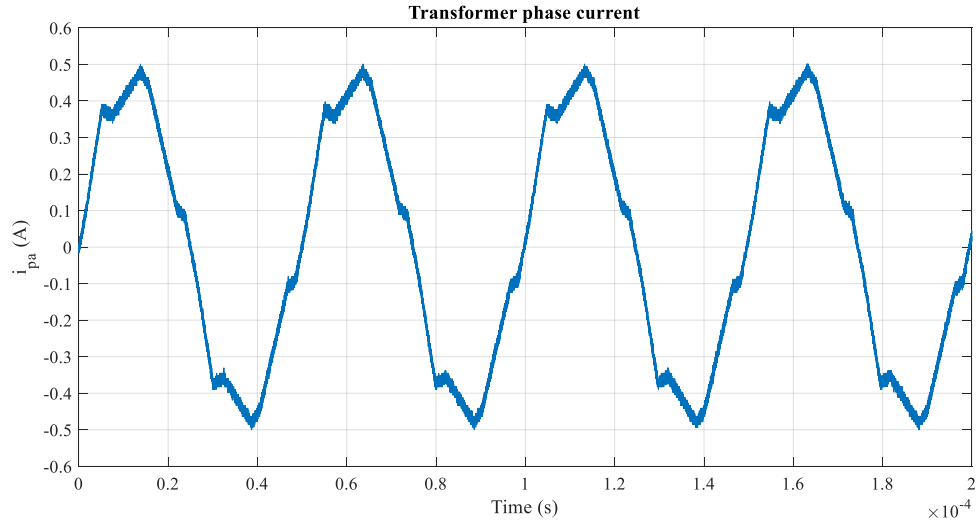


Figure 5.27 primary side AC phase current i_{pa} at normal condition

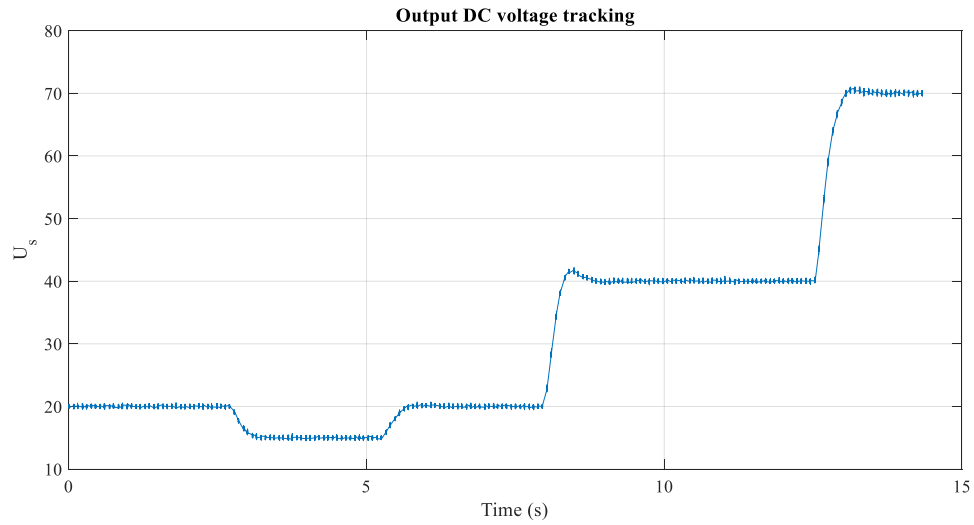


Figure 5.28 SPS voltage tracking performance

b. At fault condition

Under fault conditions, the performance of SPS control was also experimentally tested. A short circuit fault was introduced across the terminals of the DC-link capacitor. The SPS control switched from output DC voltage control to output DC current control as the voltage collapsed to zero volts. In this case study, the SPS control method is limiting the DC output current to 0.4 A, as it would be during the normal situation.

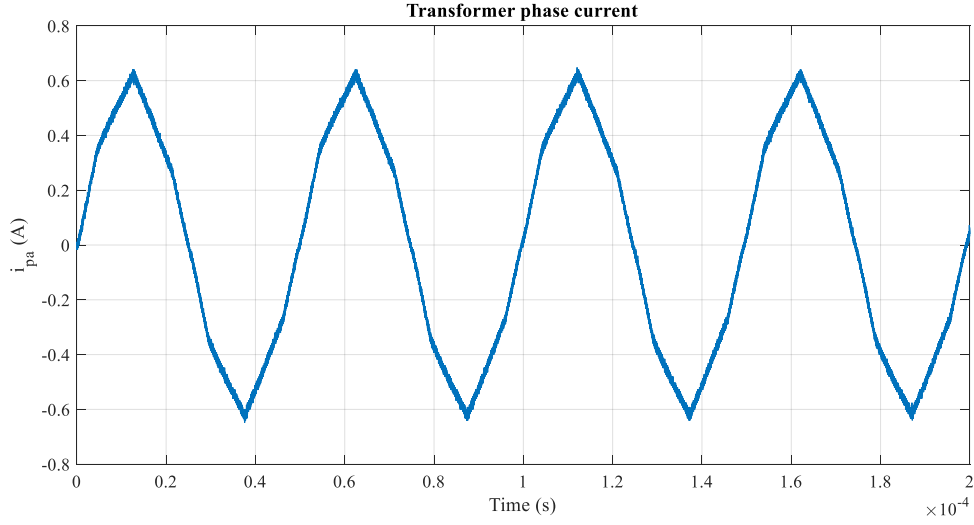


Figure 5.29 shows the primary side AC phase current of the transformer during the fault incident. Compared to Figure 5.27, we can see the increase in the peak value of the current from $i_{pa,peak} = 0.5 \text{ A}$ to $i_{pa,peak,F} = 0.63 \text{ A}$ which conforms the discussed drawback of the SPS method when dealing with faults.

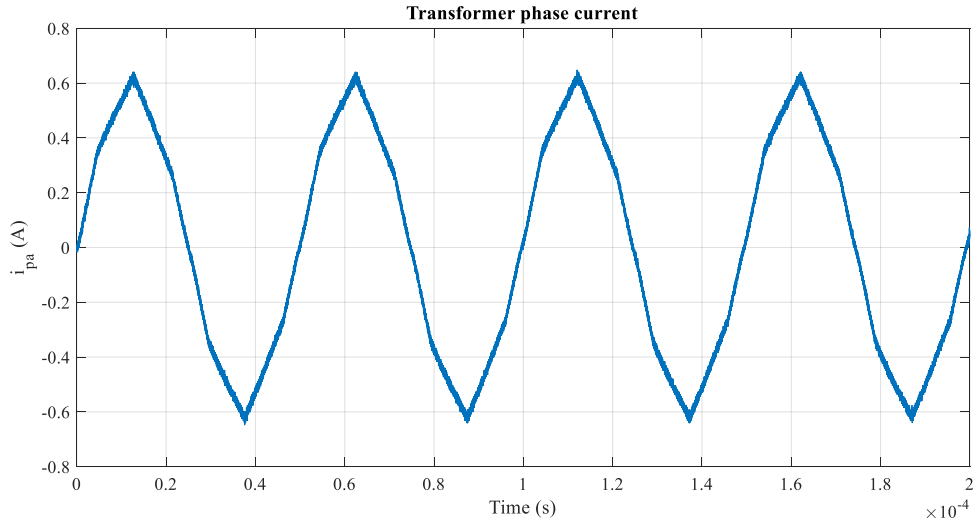


Figure 5.29 SPS phase a current i_{pa} at fault condition

5.2.2 Variable Duty Cycle Single Phase Shift Modulation

With the same procedure of the simulative validation, VDCSPS control method was experimentally examined and verified by applying it to the three-phase DAB prototype circuit after the occurrence of fault. The system will firstly run with SPS at normal conditions and then switched to VDCSPS at the instant of fault incident.

a. Case 1: zero voltage ratio fault

In this experiment for the VDCSPS method, the required peak value of the transformer AC current $i_{pa, peak}$ was set to be 0.5 A Which the peak current value at normal condition, i.e. $i_{pa, peak} = 0.5 \text{ A}$. the duty cycle was calculated to be 25% and by controlling the load angle φ the maximum output DC current is almost 0.3 A.

Figure 5.30 shows the behaviour of the three-phase DAB converter after having a short circuit fault by displaying the transformer AC primary current. We can see the peak value of the current is regulated to the predefined value, i.e. $i_{pa, peak, F} = 0.5 \text{ A}$. It can be seen that the measured waveform of the AC current has almost the same shape and values to that obtained in the simulation results with a small range of inaccuracy caused by the used measurements devices.

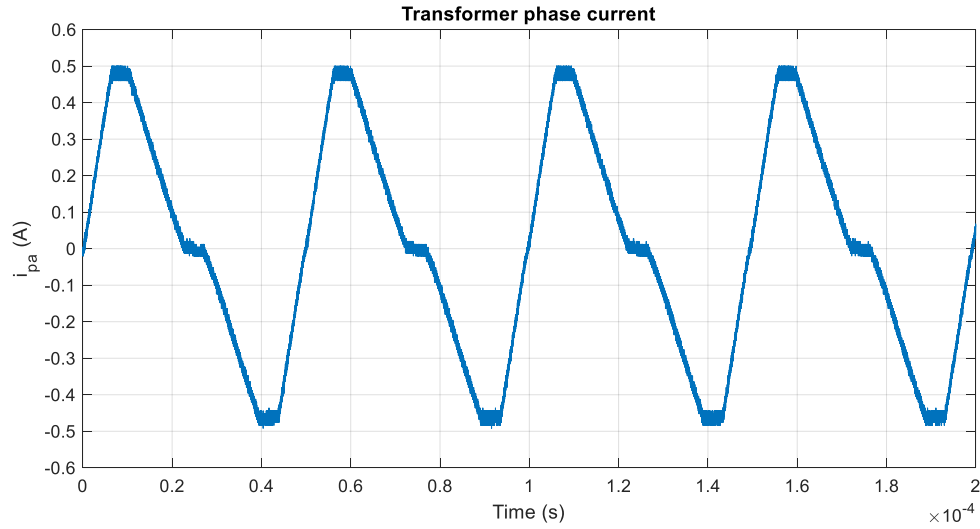


Figure 5.30 Measured primary side AC phase current i_{pa} of VDCSPS control at zero-voltage fault condition

b. Case 2: 0.1 voltage ratio fault

Additionally, the reliability of the VDCSPS was also ensured by experimentally testing the performance of the proposed control approach in case of a non- bolted fault. The same above experimental case was repeated but with a fault causing a voltage ratio of 0.1. This small voltage ratio did not cause a significant impact on the control parameters. The calculated duty cycle of this case is 25.5%. and the output DC current could reach to 0.32 A by controlling the load angle φ .

The behaviour of the three-phase DAB converter after having this 0.1 voltage-ratio fault is illustrated by displaying the transformer AC primary current as shown in Figure 5.31. We can see the peak value of the current is regulated to the predefined value, i.e. $i_{pa, peak, F} = 0.5 \text{ A}$. The waveform of the measured current is not perfect as in

simulation which is mainly due to the inaccuracy of the measuring devices available in the lab.

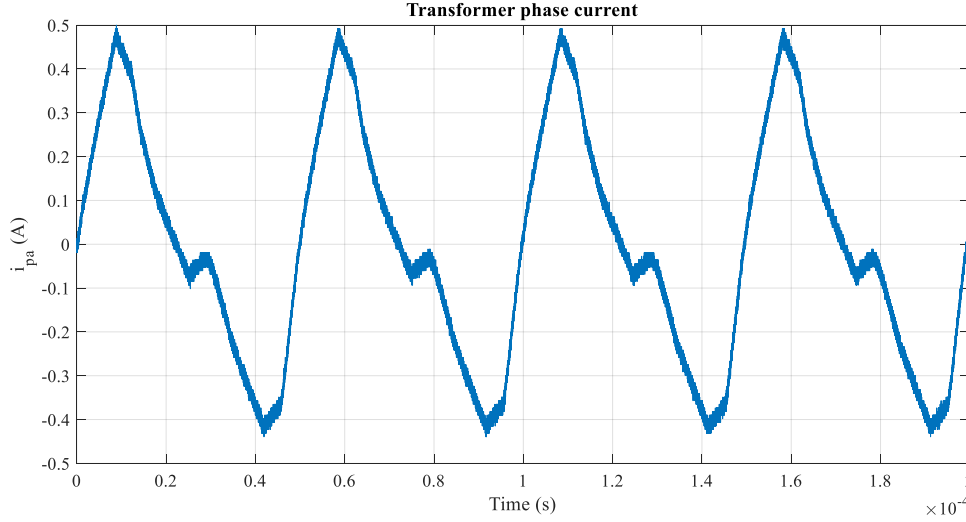


Figure 5.31 Measured primary side AC phase current i_{pa} of VDCSPS control at 0.1 voltage-ratio fault condition

5.2.3 Modified Asymmetrical Duty Cycle Modulation for Fault Control

The proposed MADCC is also verified and examined experimentally using the built experimental setup. Similar to the VDCSPS test, the three-phase DAB circuit is originally controlled using the conventional SPS modulation at normal situations. Then, at the moment of voltage collapse caused by the fault incident, the MADCC control takes charge to regulate the three-phase DAB currents.

In normal conditions, the value of AC transformer peak current $i_{sDC, peak}$ will be stored and used as a reference value for the MADCC to find the suitable control parameters. D_p , D_s , φ are obtained using (4.33), (4.34), and (4.35) to insure proper control of the peak current value, maximum output current, and soft-switching operation.

a. Case 1: zero voltage ratio fault

Since the experimental setup have the same parameters as the simulation system, the same control parameters are used in both simulation and experimental cases. the used duty cycles of the primary and secondary bridges are $D_p = 25\%$ & $D_s = 45.8\%$, while the load angle φ is determined to be equal to 1.42 rad in this case study.

By taking the measurement of the primary side AC phase current, the performance of the proposed MADCC control approach can be experimentally examined and validated. Figure 5.32 shows the primary side AC phase current which is similar to that of the VDCSPS method because they both have the same primary voltage while the secondary side voltage

is zero. We can observe that the current's peak value is restricted to the predetermined value, $i_{pa,peak,F} = 0.5 \text{ A}$. Also, the output DC current I_{sDC} was measured to be 0.4 A which is the same current value as in the normal condition. It can be seen that the measured waveform of the AC current has almost the same shape and values to that obtained in the simulation results with a small range of inaccuracy caused by the used measurements devices.

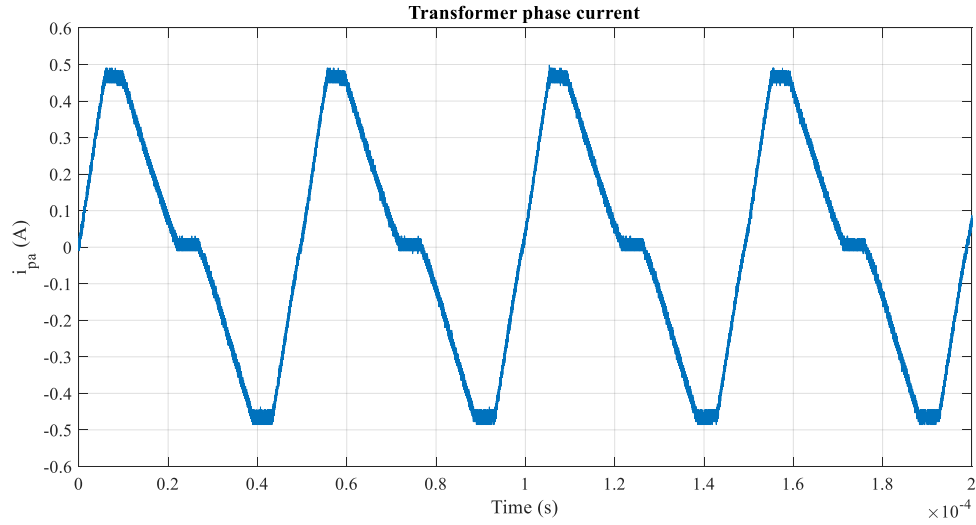


Figure 5.32 Measured primary side AC phase current i_{pa} of MADCC control at zero-voltage fault condition

b. Case 2: 0.1 voltage ratio fault

Just like VDCSPS testing approach, another case is conducted to test the MADCC performance when having non-bolted faults. The same above experimental case was repeated but with a fault causing a voltage ratio of 0.1. This small voltage ratio did not cause a significant change on the control parameters. The used duty cycles of the primary and secondary bridges are $D_p = 24.5\%$ & $D_s = 45.4\%$, while the load angle φ is determined to be equal to 1.3 rad in this case study.

By taking the measurement of the primary side AC phase current, the performance of the proposed MADCC control approach at 0.1 voltage-ratio can be experimentally examined and validated. Figure 5.33 shows the primary side AC phase current which is similar to that of the zero-voltage case as the small increase in the output voltage is still not enough to make a significant impact on the behavior of the AC currents. We can observe that the current's peak value is restricted to the predetermined value, $i_{pa,peak,F} = 0.5 \text{ A}$. Also, the output DC current I_{sDC} was measured to be 0.4 A which is the same current value as in the normal condition. It also worth mentioning that the inaccuracy in the experimental results compared to that of the simulation is mainly due to the measuring errors caused by the used measurements devices.

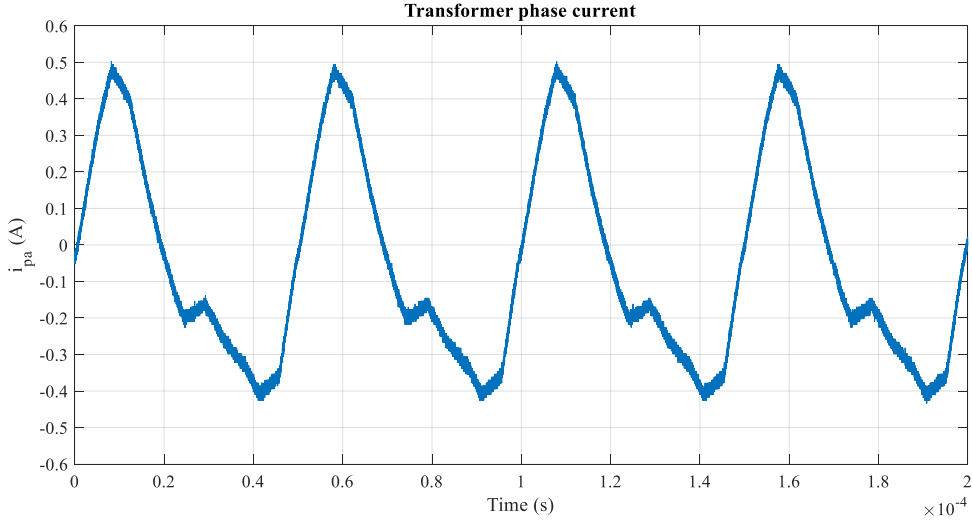


Figure 5.33 Measured primary side AC phase current i_{pa} of MADCC control at 0.1 voltage-ratio fault condition

5.3 Comparison of simulation and experimental results

For a better discrimination of the effects of each control scheme, the main simulation and experimental results obtained are compared in this section. In each validation case, both the simulation and measured waveforms of the primary AC current i_{pa} are shown in the same figure.

Starting with the conventional SPS control technique, Figure 5.34 show the simulation and experimental graphs of the primary AC current i_{pa} . The two waveforms are very similar with small difference which is due to the deviation in the system measurement devices. After the occurrence of the short circuit, the simulation and experimental signals of the primary AC current i_{pa} are shown in Figure 5.35. The two graphs are also very similar with small increase in the peak current value in the ideal simulation system.

The simulation and experimental results are also compared when the three-phase DAB is controlled using the proposed VDCSPS method. The results of this validation case are presented in Figure 5.36 and Figure 5.37 for the zero and 0.1 voltage-ratio faults, respectively. As illustrated in these two figures, the simulation and measured waveforms of the primary AC current i_{pa} are also similar with small mismatches caused by the inaccuracy of the system measurements.

Similarly, the simulation and experimental behaviours of the three-phase DAB controlled by the proposed MADCC approach are compared. The primary AC currents i_{pa} when having zero and 0.1 voltage-ratio faults are presented in Figure 5.38 and Figure 5.39. Despite the effect of the system measurements inaccuracy, the waveforms of the simulative and experimental AC current are still very similar.

This comparison strengthens the simulation and experimental verification of the performance of the conventional and proposed control schemes of the three-phase DAB converter.

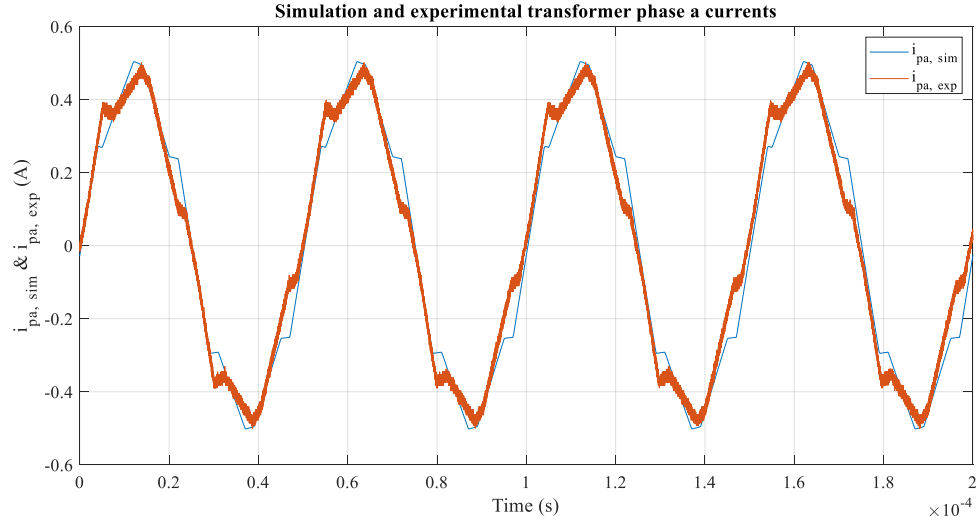


Figure 5.34 Comparison between simulation and measured primary side AC phase current i_{pa} of SPS control at normal condition

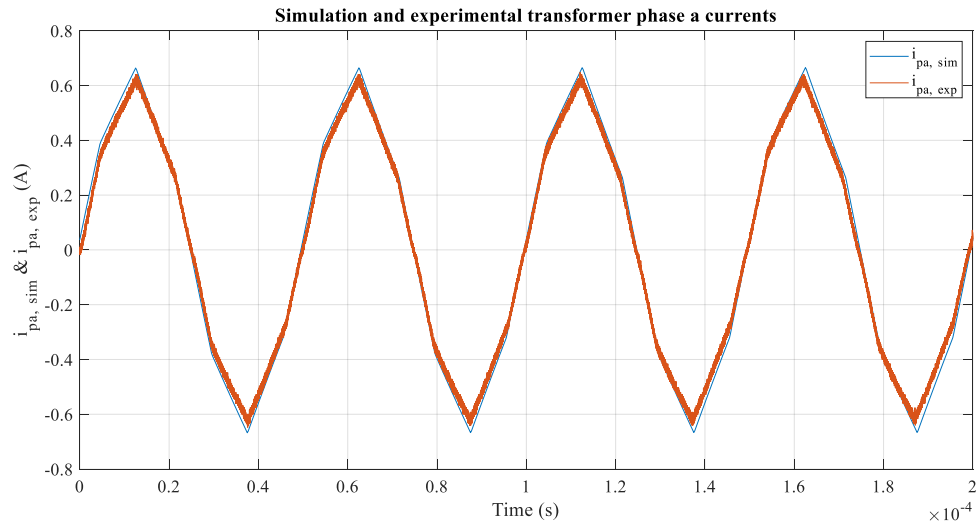


Figure 5.35 Comparison between simulation and measured primary side AC phase current i_{pa} of SPS control at fault condition

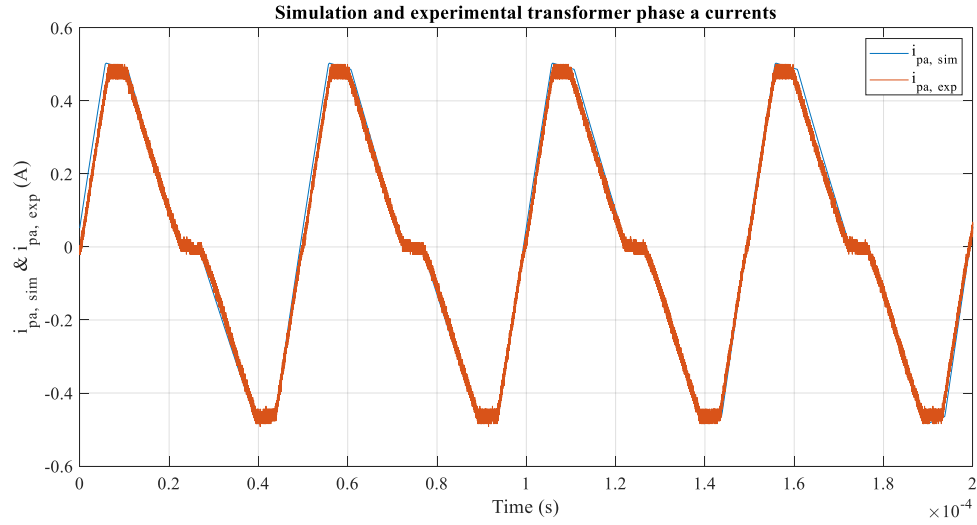


Figure 5.36 Comparison between simulation and measured primary side AC phase current i_{pa} of VDCSPS control at zero-voltage fault condition

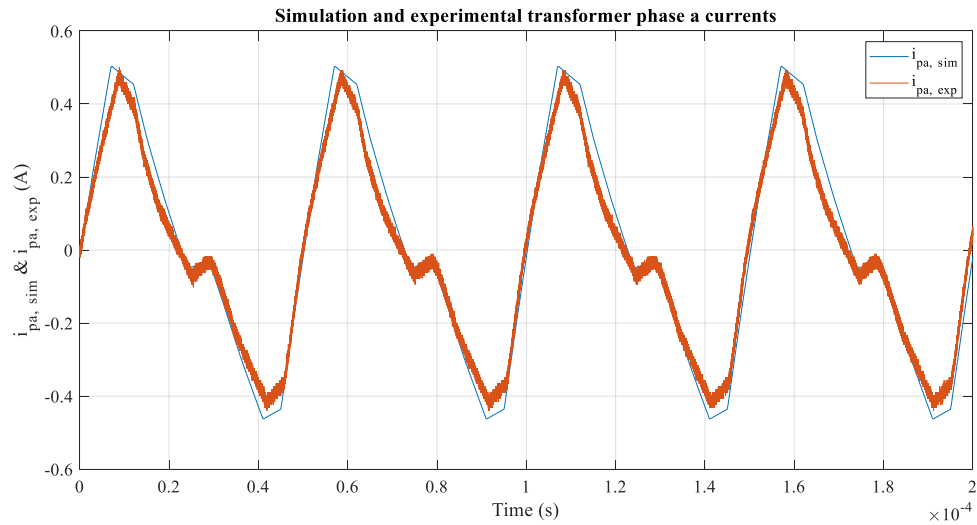


Figure 5.37 Comparison between simulation and measured primary side AC phase current i_{pa} of VDCSPS control at 0.1 voltage-ratio fault condition

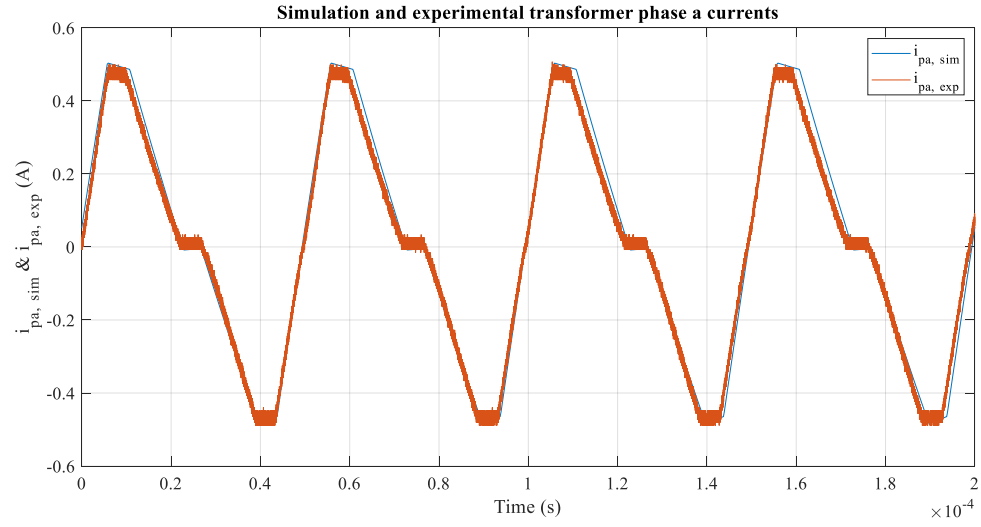


Figure 5.38 Comparison between simulation and measured primary side AC phase current i_{pa} of MADCC control at zero-voltage fault condition

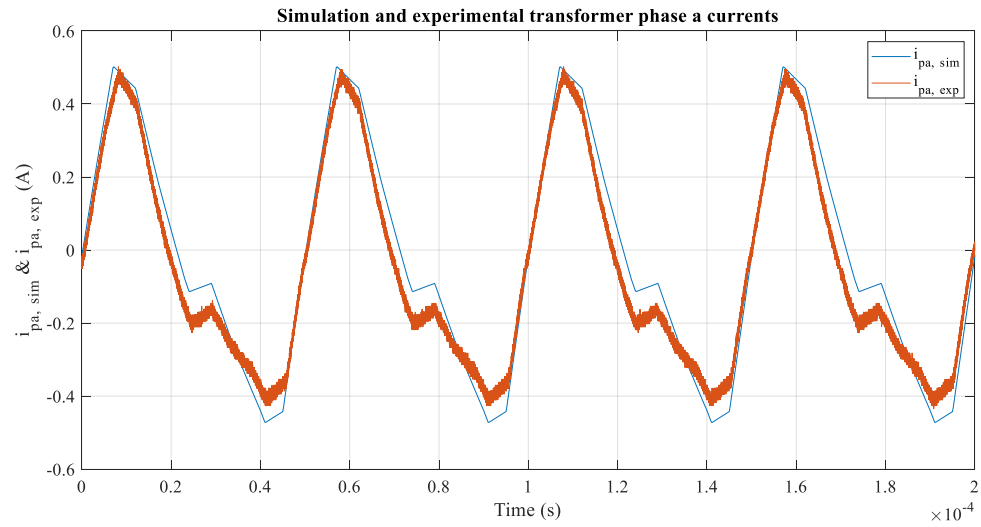


Figure 5.39 Comparison between simulation and measured primary side AC phase current i_{pa} of MADCC control at 0.1 voltage-ratio fault condition

5.4 Results comparison and discussion

All existing control schemes have some advantages and disadvantages when controlling the three-phase DAB at fault conditions and the proposed methods were suggested to overcome the drawbacks and enhance the fault ride-through capability of the converter. After obtaining the results of the proposed techniques, their advantages and limitations can be discussed and compared to those of the conventional control schemes.

As has been shown in the simulation and experimental results of the SPS control method, SPS is a very effective modulation strategy for output voltage regulation, high power transfer, and soft switching operation. However, at fault situations, the peak value of the AC current increases significantly which increases the amount of power loss and thermal stress on the switches that can damage these switches. As a result, SPS modulation is not suitable for fault ride through operation.

ADCC is also an effective modulation technique for voltage regulation while maintaining soft switching operation. The issue with ADCC method is the lower power transfer and the apparent inability on delivering output current at zero-voltage faults. The space vector ADCC is an adjusted version of the ADCC that can deliver high output current, close to normal, at zero-voltage faults. However, this method has only one control parameter which is the duty cycle of the primary bridge D_p .

It has been proven in the simulation and experimental results that the proposed VDCSPS approach effectively solves the high peak value of the AC current issue and regulates the output DC current. It also enables the three-phase DAB to deliver output current at zero-voltage faults. However, this output current is not that high and might not be enough for fault detection. Also, half of the converter periodic switching operation suffers from hard switching operations.

The proposed MADCC modulation method overcomes the aforementioned drawbacks of the space vector ADCC and the VDCSPS while maintaining the advantages. This method has three independent control parameters, which are the load angle φ and the primary and secondary duty cycles, D_p and D_s which provides more freedom to adjust the transformer current and transferred power. Besides the effective regulation of the transformer AC phase current, this method enables high output current that is close to that in normal conditions. Finally, all converter switches have soft switching turn ons and offs except for the turn offs of the primary bridge switches. All these advantages make the proposed MADCC to be the most suitable modulation technique for the three-phase DAB under fault conditions.

Table 5.3 summarizes the comparison between the modulation approaches for controlling the fault current of the three-phase DAB.

Table 5.3: Comparison of the control methods of the three-phase DAB

Control method	Phase current	Control Parameters	Output DC current	Soft switching
SPS	High	One (φ)	Same as normal	18/24 operations
Space vector ADCC	Regulated	One (D_p)	Lower than Normal	18/24 operations
VDCSPS	Regulated	Two (D & φ)	Much lower than Normal	12/24 operations
MADCC	Regulated	Three (D_p , D_s & φ)	Close to normal	18/24 operations

CHAPTER 6

CONCLUSION & FUTURE WORK

Towards developing breaker-less protection systems for DC grids. The various control and modulation schemes for the three-phase dual-active bridge (DAB) converter were investigated in this thesis. Because short-circuit fault current develops significantly faster in dc grids than in ac grids, putting power-electronics interfaced energy sources and loads at risk, the three-phase DAB converter's dc fault ride-through (FRT) capability is essential to limit fault current in dc grids. However, the existing single-phase shift (SPS) as well as the asymmetrical duty cycle control schemes exhibit some major drawbacks and limitation especially at zero-voltage fault incidents. Solving these drawbacks was the aim of this thesis. The thesis work and contribution are summarized as follows:

- The existing modulation techniques for the three-phase DAB were comprehensively studied and their different features and limitation were highlighted.
- Two new modulation techniques were proposed to significantly improve the performance of the three-phase DAB at fault conditions.
- The proposed modulation methods were theoretically derived and validated using both simulation and experimental testing.
- Using these simulation and experimental results, the proposed and existing control schemes were compared, and the drawbacks of the existing methods were verified to be overcome. This will enable the three-phase DAB converter to ride through faults and the entire DC microgrid to dispense with all kinds of circuit breakers.

The research can be furtherly enhanced by studying the following research topics:

- **Optimized design of the transformer of the three-phase DAB transformer**
The performance of the three-phase DAB can be enhanced by optimally choosing the transformer's type, core, size, leakage and magnetizing inductances and impedances.
- **Optimized design of the DC-link capacitor of the three-phase DAB transformer**
When a breaker-less dc grid has a dc short-circuit fault, the grid-connected converters' dc-link filter capacitors are discharged very fast, resulting in a hazard surge current. The dc-link capacitance of power converters must be decreased to reduce the impact of the capacitor discharging current on other devices. Dc-link

filter capacitors, on the other hand, are critical for maintaining dc grid voltage regulation. As a result, a systematic method is needed to study and improve the stability of breaker-less dc grids, as well as to optimize the design of dc-link filters while taking into account the trade-off between system stability and dc fault current.

- **Complete implementation of a proper breaker-less protection scheme for DC microgrids**

A complete three-phase DAB-based DC microgrid needs to be built with several sources and loads. After deep study of the existing integrated breaker-less protection schemes that include detection, location and isolation of faults, more sophisticated protection scheme can be develop taking advantage of the fault ride through capability discussed in this thesis.

References

- [1] P. Fairley, “DC versus AC: The second war of currents has already begun [in my view],” *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 103–104, 2012, doi: 10.1109/MPE.2012.2212617.
- [2] X. Liu, P. Wang, and P. C. Loh, “A hybrid AC/DC micro-grid,” *2010 9th Int. Power Energy Conf. IPEC 2010*, pp. 746–751, 2010, doi: 10.1109/IPECON.2010.5697024.
- [3] A. T. Elsayed, A. A. Mohamed, and O. A. Mohammed, “DC microgrids and distribution systems: An overview,” *Electr. Power Syst. Res.*, vol. 119, pp. 407–417, 2015, doi: 10.1016/j.epsr.2014.10.017.
- [4] N. Bayati, A. Hajizadeh, and M. Soltani, “Protection in DC microgrids: a comparative review,” *IET Smart Grid*, vol. 1, no. 3, pp. 66–75, Oct. 2018, doi: 10.1049/iet-stg.2018.0035.
- [5] G. K. Rao and P. Jena, “Fault Detection in DC Microgrid Based on the Resistance Estimation,” *IEEE Syst. J.*, 2021, doi: 10.1109/JSYST.2020.3046054.
- [6] V. Mortezapour and H. Lesani, “Hybrid AC/DC microgrids: A generalized approach for autonomous droop-based primary control in islanded operations,” *Int. J. Electr. Power Energy Syst.*, vol. 93, pp. 109–118, 2017, doi: 10.1016/j.ijepes.2017.05.022.
- [7] F. Bodi and E. H. Lim, “380/400V DC powering option,” *INTELEC, Int. Telecommun. Energy Conf.*, pp. 1–8, 2011, doi: 10.1109/INTLEC.2011.6099885.
- [8] V. A. Prabhala, B. P. Baddipadiga, P. Fajri, and M. Ferdowsi, “An overview of direct current distribution system architectures & benefits,” *Energies*, vol. 11, no. 9, 2018, doi: 10.3390/en11092463.
- [9] W. M. Hamanah, M. A. Abido, and L. M. Alhems, “Optimum Sizing of Hybrid PV, Wind, Battery and Diesel System Using Lightning Search Algorithm,” *Arab. J. Sci. Eng.*, vol. 45, no. 3, pp. 1871–1883, 2020, doi: 10.1007/s13369-019-04292-w.
- [10] S. Beheshtaein, R. M. Cuzner, M. Forouzesh, M. Savaghebi, and J. M. Guerrero, “DC Microgrid Protection: A Comprehensive Review,” *IEEE J. Emerg. Sel. Top. Power Electron.*, pp. 1–1, Mar. 2019, doi: 10.1109/jestpe.2019.2904588.
- [11] M. Mobarrez, “DC Microgrids: Architectures, Control and Economic Analysis,” North Carolina State University, 2018.
- [12] D. Bharti and M. De, “Planning Framework for Optimal Resource Utilization Strategy in Microgrid,” *Arab. J. Sci. Eng.*, vol. 45, no. 3, pp. 1927–1947, 2020,

doi: 10.1007/s13369-019-04310-x.

- [13] G. Ensermu, A. Bhattacharya, and N. Panigrahy, “Real-Time Simulation of Smart DC Microgrid with Decentralized Control System Under Source Disturbances,” *Arab. J. Sci. Eng.*, vol. 44, no. 8, pp. 7173–7185, 2019, doi: 10.1007/s13369-019-03842-6.
- [14] D. Kumar, F. Zare, and A. Ghosh, “DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects,” *IEEE Access*, vol. 5, pp. 12230–12256, 2017, doi: 10.1109/ACCESS.2017.2705914.
- [15] W. Javed, D. Chen, M. E. Farrag, and Y. Xu, “System configuration, fault detection, location, isolation and restoration: A review on LVDC microgrid protections,” *Energies*, vol. 12, no. 6. MDPI AG, 2019, doi: 10.3390/en12061001.
- [16] A. Chandra, G. K. Singh, and V. Pant, “Protection techniques for DC microgrid- A review,” *Electr. Power Syst. Res.*, vol. 187, no. May, p. 106439, 2020, doi: 10.1016/j.epsr.2020.106439.
- [17] M. Gomes, P. Coelho, and C. Moreira, “Microgrid protection schemes,” *Microgrids Des. Implement.*, no. Lv, pp. 311–336, 2018, doi: 10.1007/978-3-319-98687-6_12.
- [18] D. Salomonsson, L. Söder, and A. Sannino, “Protection of low-voltage DC microgrids,” *IEEE Trans. Power Deliv.*, vol. 24, no. 3, pp. 1045–1053, 2009, doi: 10.1109/TPWRD.2009.2016622.
- [19] A. Meghwani, S. C. Srivastava, and S. Chakrabarti, “A new protection scheme for DC microgrid using line current derivative,” *IEEE Power Energy Soc. Gen. Meet.*, vol. 2015-Septe, pp. 1–5, 2015, doi: 10.1109/PESGM.2015.7286041.
- [20] I. IEEE Industrial Electronics Society. Conference (42nd : 2016 : Florence, Institute of Electrical and Electronics Engineers, and IEEE Industrial Electronics Society, *Proceedings of the IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society : Florence (Italy), October 24-27, 2016.* .
- [21] A. Q. Huang, “Medium-Voltage Solid-State Transformer: Technology for a Smarter and Resilient Grid,” *IEEE Ind. Electron. Mag.*, vol. 10, no. 3, pp. 29–42, Sep. 2016, doi: 10.1109/MIE.2016.2589061.
- [22] D. Wang, A. Emhemed, P. Norman, and G. Burt, “Evaluation of existing DC protection solutions on an active LVDC distribution network under different fault conditions,” in *CIREN - Open Access Proceedings Journal*, 2017, vol. 2017, no. 1, pp. 1112–1116, doi: 10.1049/oap-cired.2017.0673.
- [23] J. Do Park and J. Candelaria, “Fault detection and isolation in low-voltage dc-bus microgrid system,” *IEEE Trans. Power Deliv.*, vol. 28, no. 2, pp. 779–787, 2013, doi: 10.1109/TPWRD.2013.2243478.

- [24] M. Monadi, M. A. Zamani, J. I. Candela, A. Luna, and P. Rodriguez, "Protection of AC and DC distribution systems Embedding distributed energy resources: A comparative review and analysis," *Renewable and Sustainable Energy Reviews*, vol. 51. Elsevier Ltd, pp. 1578–1593, 03-Aug-2015, doi: 10.1016/j.rser.2015.07.013.
- [25] D. Wang, A. A. S. Emhemed, and G. M. Burt, "Improved voltage-based protection scheme for an LVDC distribution network interfaced by a solid state smart transformer," *IET Gener. Transm. Distrib.*, vol. 13, no. 21, pp. 4821–4829, Nov. 2019, doi: 10.1049/iet-gtd.2019.0544.
- [26] S. D. A. Fletcher, P. J. Norman, S. J. Galloway, and G. M. Burt, "Determination of protection system requirements for DC unmanned aerial vehicle electrical power networks for enhanced capability and survivability," *IET Electr. Syst. Transp.*, vol. 1, no. 4, pp. 137–147, Dec. 2011, doi: 10.1049/iet-est.2010.0070.
- [27] D. K. J. S. Jayamaha, N. W. A. Lidula, and A. D. Rajapakse, "Protection and grounding methods in DC microgrids: Comprehensive review and analysis," *Renew. Sustain. Energy Rev.*, vol. 120, no. February 2019, p. 109631, 2020, doi: 10.1016/j.rser.2019.109631.
- [28] J. Yang, J. E. Fletcher, and J. O'Reilly, "Short-circuit and ground fault analyses and location in VSC-based DC network cables," *IEEE Trans. Ind. Electron.*, vol. 59, no. 10, pp. 3827–3837, 2012, doi: 10.1109/TIE.2011.2162712.
- [29] S. Mirsaeidi, D. Mat Said, M. Wazir Mustafa, M. Hafiz Habibuddin, and K. Ghaffari, "Progress and problems in micro-grid protection schemes," *Renewable and Sustainable Energy Reviews*. 2014, doi: 10.1016/j.rser.2014.05.044.
- [30] N. Amleh, M. AlMuhaini, and M. Khalid, "Impact of Smart Restoration and Energy Storage Systems on the Reliability of Electric Microgrid," *Arab. J. Sci. Eng.*, vol. 45, no. 3, pp. 1911–1925, 2020, doi: 10.1007/s13369-019-04288-6.
- [31] W. Li, A. Monti, and F. Ponci, "Fault detection and classification in medium voltage dc shipboard power systems with wavelets and artificial neural networks," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 11, pp. 2651–2665, Nov. 2014, doi: 10.1109/TIM.2014.2313035.
- [32] J. C. Hernandez, F. S. Sutil, and P. G. Vidal, "Protection of a multiterminal DC compact node feeding electric vehicles on electric railway systems, secondary distribution networks, and PV systems," *Turkish J. Electr. Eng. Comput. Sci.*, vol. 24, no. 4, pp. 3123–3143, 2016, doi: 10.3906/elk-1406-14.
- [33] M. E. Baran and N. R. Mahajan, "Overcurrent protection on voltage-source-converter-based multiterminal DC distribution systems," *IEEE Trans. Power Deliv.*, vol. 22, no. 1, pp. 406–412, 2007, doi: 10.1109/TPWRD.2006.877086.
- [34] L. Qi, A. Antoniazzi, and L. Raciti, "DC Distribution Fault Analysis, Protection Solutions, and Example Implementations," *IEEE Trans. Ind. Appl.*, vol. 54, no. 4,

- pp. 3179–3186, 2018, doi: 10.1109/TIA.2018.2825437.
- [35] W. Wen *et al.*, “Analysis and Experiment of a Micro-Loss Multi-Port Hybrid DCCB for MVDC Distribution System,” *IEEE Trans. Power Electron.*, vol. 34, no. 8, pp. 7933–7941, Aug. 2019, doi: 10.1109/TPEL.2018.2881000.
 - [36] O. V. Gnana Swathika and S. Hemamalini, “Prims-Aided Dijkstra Algorithm for Adaptive Protection in Microgrids,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 4, no. 4, pp. 1279–1286, Dec. 2016, doi: 10.1109/JESTPE.2016.2581986.
 - [37] S. Teimourzadeh, F. Aminifar, M. Davarpanah, and J. M. Guerrero, “Macroprotections for Microgrids: Toward a New Protection Paradigm Subsequent to Distributed Energy Resource Integration,” *IEEE Ind. Electron. Mag.*, vol. 10, no. 3, pp. 6–18, Sep. 2016, doi: 10.1109/MIE.2016.2569620.
 - [38] S. D. A. Fletcher, P. J. Norman, S. J. Galloway, P. Crolla, and G. M. Burt, “Optimizing the roles of unit and non-unit protection methods within DC microgrids,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2079–2087, 2012, doi: 10.1109/TSG.2012.2198499.
 - [39] A. Meghwani, S. C. Srivastava, and S. Chakrabarti, “Local measurement-based technique for estimating fault location in multi-source DC microgrids,” *IET Gener. Transm. Distrib.*, vol. 12, no. 13, pp. 3305–3313, 2018, doi: 10.1049/iet-gtd.2017.1801.
 - [40] IEEE Electrical Insulation Society Staff, *2013 IEEE Electric Ship Technologies Symposium (ESTS)*. .
 - [41] K. A. Saleh, A. Hooshyar, and E. F. El-Saadany, “Hybrid Passive-Overcurrent Relay for Detection of Faults in Low-Voltage DC Grids,” *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1129–1138, 2017, doi: 10.1109/TSG.2015.2477482.
 - [42] A. Meghwani, S. C. Srivastava, and S. Chakrabarti, “A Non-unit Protection Scheme for DC Microgrid Based on Local Measurements,” *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 172–181, 2017, doi: 10.1109/TPWRD.2016.2555844.
 - [43] A. Meghwani, R. Gokaraju, S. C. Srivastava, and S. Chakrabarti, “Local Measurements-Based Backup Protection for DC Microgrids Using Sequential Analyzing Technique,” *IEEE Syst. J.*, pp. 1–12, 2019, doi: 10.1109/JSYST.2019.2919144.
 - [44] R. Mohanty and A. K. Pradhan, “Protection of smart DC microgrid with ring configuration using parameter estimation approach,” *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6328–6337, Nov. 2018, doi: 10.1109/TSG.2017.2708743.
 - [45] A. A. S. Emhemed, K. Fong, S. Fletcher, and G. M. Burt, “Validation of fast and selective protection scheme for an LVDC distribution network,” *IEEE Trans. Power Deliv.*, vol. 32, no. 3, pp. 1432–1440, Jun. 2017, doi: 10.1109/TPWRD.2016.2593941.

- [46] R. Mohanty and A. K. Pradhan, "A Superimposed Current Based Unit Protection Scheme for DC Microgrid," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3917–3919, Jul. 2018, doi: 10.1109/TSG.2018.2835645.
- [47] S. Ahmadi, I. Sadeghkhani, G. Shahgholian, B. Fani, and J. M. Guerrero, "Protection of LVDC Microgrids in Grid-Connected and Islanded Modes Using Bifurcation Theory," *IEEE J. Emerg. Sel. Top. Power Electron.*, pp. 1–1, Dec. 2019, doi: 10.1109/jestpe.2019.2961903.
- [48] M. Monadi, C. Gavriluta, A. Luna, J. I. Candela, and P. Rodriguez, "Centralized protection strategy for medium voltage DC microgrids," *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 430–440, 2017, doi: 10.1109/TPWRD.2016.2600278.
- [49] S. D. A. Fletcher, P. J. Norman, K. Fong, S. J. Galloway, and G. M. Burt, "High-speed differential protection for smart DC distribution systems," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2610–2617, 2014, doi: 10.1109/TSG.2014.2306064.
- [50] S. Dhar, R. K. Patnaik, and P. K. Dash, "Fault Detection and Location of Photovoltaic Based DC Microgrid Using Differential Protection Strategy," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4303–4312, 2018, doi: 10.1109/TSG.2017.2654267.
- [51] P. Cairoli and R. A. Dougal, "Fault detection and isolation in medium-voltage DC microgrids: Coordination between supply power converters and bus contactors," *IEEE Trans. Power Electron.*, vol. 33, no. 5, pp. 4535–4546, May 2018, doi: 10.1109/TPEL.2017.2724145.
- [52] N. Bayati, H. R. Baghaee, A. Hajizadeh, and M. Soltani, "Localized protection of radial DC microgrids with high penetration of constant power loads," *IEEE Syst. J.*, 2020, doi: 10.1109/JSYST.2020.2998059.
- [53] Y. Yang, C. Huang, and Q. Xu, "A Fault Location Method Suitable for Low-Voltage DC Line," *IEEE Trans. Power Deliv.*, vol. 35, no. 1, pp. 194–204, Feb. 2020, doi: 10.1109/TPWRD.2019.2930622.
- [54] K. Jia, M. Li, T. S. Bi, and Q. X. Yang, "A voltage resonance-based single-ended online fault location algorithm for DC distribution networks," *Sci. China Technol. Sci.*, vol. 59, no. 5, pp. 721–729, May 2016, doi: 10.1007/s11431-016-6033-2.
- [55] M. Ikhide, S. B. Tennakoon, H. Ha, A. L. Griffiths, S. Subramanian, and A. J. Adamczyk, "A transient and non-unit-based protection technique for DC grids based on the rate-of-change (R-o-C) of the fault induced travelling wave components," *Sustain. Energy, Grids Networks*, vol. 17, p. 100195, 2019, doi: 10.1016/j.segan.2019.100195.
- [56] C. Zhang, G. Song, L. Yang, and X. Dong, "Non-unit travelling wave protection method for dc transmission line using waveform correlation calculation," *IET Gener. Transm. Distrib.*, vol. 14, no. 12, pp. 2263–2270, 2020, doi: 10.1049/iet-gtd.2019.0455.

- [57] J. Wu, H. Li, G. Wang, and Y. Liang, "An Improved Traveling-Wave Protection Scheme for LCC-HVDC Transmission Lines," *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 106–116, Feb. 2017, doi: 10.1109/TPWRD.2016.2549565.
- [58] P. Jafarian and M. Sanaye-Pasand, "A traveling-wave-based protection technique using wavelet/pca analysis," *IEEE Trans. Power Deliv.*, vol. 25, no. 2, pp. 588–599, Apr. 2010, doi: 10.1109/TPWRD.2009.2037819.
- [59] S. Z. Jamali *et al.*, "Protection scheme of a last mile active LVDC distribution network with reclosing option," *Energies*, vol. 11, no. 5, 2018, doi: 10.3390/en11051093.
- [60] K. A. Saleh, A. Hooshyar, and E. F. El-Saadany, "Ultra-high-speed traveling-wave-based protection scheme for medium-voltage DC microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 1440–1451, 2019, doi: 10.1109/TSG.2017.2767552.
- [61] K. Saleh, A. Hooshyar, and E. F. El-saadany, "Fault detection and location in medium- voltage DC microgrids using travelling-wave reflections," pp. 1–9, 2020, doi: 10.1049/iet-rpg.2019.0370.
- [62] S. S. Nagam, R. K. Panda, A. Mohapatra, and S. Anand, "Gaussian Process Regression based Fault Location in DC Microgrid," pp. 1–6.
- [63] I. M. Karmacharya and R. Gokaraju, "Fault Location in Ungrounded Photovoltaic System Using Wavelets and ANN," *IEEE Trans. Power Deliv.*, vol. 33, no. 2, pp. 549–559, Apr. 2018, doi: 10.1109/TPWRD.2017.2721903.
- [64] Q. Yang, J. Li, S. Le Blond, and C. Wang, "Artificial Neural Network Based Fault Detection and Fault Location in the DC Microgrid," in *Energy Procedia*, 2016, vol. 103, pp. 129–134, doi: 10.1016/j.egypro.2016.11.261.
- [65] L. Guomin, T. Yingjie, Y. Changyuan, L. Yinglin, and H. Jinghan, "Deep learning-based fault location of DC distribution networks," vol. 2019, no. Acdc 2018, pp. 3301–3305, 2019, doi: 10.1049/joe.2018.8902.
- [66] H. Pugliese and M. Von Kanneurff, "Discovering DC: A primer on dc circuit breakers, their advantages, and design," *IEEE Ind. Appl. Mag.*, vol. 19, no. 5, pp. 22–28, 2013, doi: 10.1109/MIAS.2012.2215992.
- [67] L. Tang and B. T. Ooi, "Locating and isolating DC faults in multi-terminal DC systems," *IEEE Trans. Power Deliv.*, vol. 22, no. 3, pp. 1877–1884, 2007, doi: 10.1109/TPWRD.2007.899276.
- [68] L. Dewan, *Lecture Notes in Electrical Engineering 667 Advances in Renewable Energy and Sustainable Environment*. 2019.
- [69] R. Cuzner, D. MacFarlin, D. Clinger, M. Rumney, and G. Castles, "Circuit breaker protection considerations in power converter-fed dc systems," in *IEEE Electric Ship Technologies Symposium, ESTS 2009*, 2009, pp. 360–367, doi: 10.1109/ESTS.2009.4906537.

- [70] C. M. Franck, "HVDC circuit breakers: A review identifying future research needs," *IEEE Trans. Power Deliv.*, vol. 26, no. 2, pp. 998–1007, 2011, doi: 10.1109/TPWRD.2010.2095889.
- [71] X. Pei, O. Cwikowski, D. S. Vilchis-Rodriguez, M. Barnes, A. C. Smith, and R. Shuttleworth, "A review of technologies for MVDC circuit breakers," *IECON Proc. (Industrial Electron. Conf.)*, vol. 0, pp. 3799–3805, 2016, doi: 10.1109/IECON.2016.7793492.
- [72] T. Schultz, P. Herzog, and C. M. Franck, "Interruption limits of mechanical circuit breakers and circuit upgrades for current injection in HVDC circuit breakers," *High Volt.*, vol. 5, no. 3, pp. 334–342, 2020, doi: 10.1049/hve.2019.0119.
- [73] Gazi Üniversitesi, Aksaray Üniversitesi, University of Buner, P. International Islamic University (Islāmābād, Institute of Electrical and Electronics Engineers. Turkey Section, and Institute of Electrical and Electronics Engineers, *2nd International Conference on Electrical, Communication, and Computer Engineering (ICECCE 2020) : 12th-13th June 2020, Istanbul, Turkey.* .
- [74] Z. J. Shen, G. Sabui, Z. Miao, and Z. Shuai, "Wide-bandgap solid-state circuit breakers for DC power systems: Device and circuit considerations," *IEEE Trans. Electron Devices*, vol. 62, no. 2, pp. 294–300, 2015, doi: 10.1109/TED.2014.2384204.
- [75] I. Almutairy, "Solid state circuit breaker protection devices for DC microgrid in review," *2016 5th Int. Conf. Electron. Devices, Syst. Appl.*, pp. 1–3, 2017, doi: 10.1109/icedsa.2016.7818478.
- [76] T. Pang, M. F. Rahman, and M. D. Manjrekar, "A Ground Clamped Solid-State Circuit Breaker for DC Distribution Systems," pp. 989–994, 2020, doi: 10.1109/ecce44975.2020.9235824.
- [77] K. Sano and M. Takasaki, "A surgeless solid-state DC circuit breaker for voltage-source-converter- based HVDC systems," *IEEE Trans. Ind. Appl.*, vol. 50, no. 4, pp. 2690–2699, 2014, doi: 10.1109/TIA.2013.2293819.
- [78] A. Shukla and G. D. Demetriades, "A Survey on Hybrid Circuit-Breaker Topologies," *IEEE Trans. Power Deliv.*, vol. 30, no. 2, pp. 627–641, 2015, doi: 10.1109/TPWRD.2014.2331696.
- [79] M. Callavik and A. Blomberg, "Hybrid DC Breaker," pp. 1–10, 2012.
- [80] Y. Bingjian, G. Yang, W. Xiaoguang, H. Zhiyuan, C. Longlong, and S. Yunhai, "A hybrid circuit breaker for DC-application," *2015 IEEE 1st Int. Conf. Direct Curr. Microgrids, ICDCM 2015*, pp. 187–192, 2015, doi: 10.1109/ICDCM.2015.7152036.
- [81] K. A. Corzine and R. W. Ashton, "A new Z-source DC circuit breaker," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2796–2804, 2012, doi:

10.1109/TPEL.2011.2178125.

- [82] V. R. I, S. N. Banavath, and S. Thamballa, “Modified z-Source DC Circuit Breaker with Enhanced Performance during Commissioning and Reclosing,” *IEEE Trans. Power Electron.*, vol. 37, no. 1, pp. 910–919, 2021, doi: 10.1109/TPEL.2021.3092773.
- [83] D. C. M. Protection, “Novel Bidirectional O- Z -Source Circuit Breaker for,” vol. 36, no. 2, pp. 1602–1613, 2021.
- [84] V. R. I, B. S. Naik, and T. Sreekanth, “Modified Z-Source DC Circuit Breaker with Zero Negative Current in the Load,” pp. 1548–1553, 2021, doi: 10.1109/ecce-asia49820.2021.9478982.
- [85] K. Subramaniam and M. S. Illindala, “Intelligent three tie contactor switch unit-based fault detection and isolation in dc microgrids,” in *IEEE Transactions on Industry Applications*, 2020, vol. 56, no. 1, pp. 95–105, doi: 10.1109/TIA.2019.2948923.
- [86] P. Cairolì, R. Rodrigues, and H. Zheng, “Fault current limiting power converters for protection of DC microgrids,” *Conf. Proc. - IEEE SOUTHEASTCON*, 2017, doi: 10.1109/SECON.2017.7925392.
- [87] D. D. C. Lu, J. L. Soon, and D. Verstraete, “Derivation of dual-switch step-down DC/DC converters with fault-tolerant capability,” *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6064–6068, 2016, doi: 10.1109/TPEL.2016.2530853.
- [88] L. Shulin, L. Jian, Y. Yang, and J. Zhong, “Design of intrinsically safe buck DC/DC converters,” *ICEMS 2005 Proc. Eighth Int. Conf. Electr. Mach. Syst.*, vol. 2, no. Ccm, pp. 1327–1331, 2005, doi: 10.1109/icems.2005.202763.
- [89] Z. Xiao, “An Instantaneously Triggered Short-Circuit Protection Architecture for Boost Switching DC/DC Converters,” *IEEE Trans. Power Electron.*, vol. 33, no. 7, pp. 5677–5685, 2018, doi: 10.1109/TPEL.2017.2743170.
- [90] C. Chen, G. P. Adam, S. Finney, J. Fletcher, and B. Williams, “H-bridge modular multi-level converter: Control strategy for improved DC fault ride-through capability without converter blocking,” *IET Power Electron.*, vol. 8, no. 10, pp. 1996–2008, 2015, doi: 10.1049/iet-pel.2014.0513.
- [91] M. López, A. Rodríguez, E. Blanco, M. Saeed, Á. Martínez, and F. Briz, “Design and implementation of the control of an MMC-based solid state transformer,” *Proceeding - 2015 IEEE Int. Conf. Ind. Informatics, INDIN 2015*, no. August 2017, pp. 1583–1590, 2015, doi: 10.1109/INDIN.2015.7281970.
- [92] R. W. A. A. De Doncker, D. M. Divan, and M. H. Kheraluwala, “A Three-Phase Soft-Switched High-Power-Density DC/DC Converter for High-Power Applications,” *IEEE Trans. Ind. Appl.*, vol. 27, no. 1, pp. 63–73, 1991, doi: 10.1109/28.67533.

- [93] J. Hu, S. Cui, and R. W. De Doncker, "DC Fault Ride-Through of a Three-Phase Dual-Active Bridge Converter for DC Grids," *2018 Int. Power Electron. Conf. IPEC-Niigata - ECCE Asia 2018*, pp. 2250–2256, 2018, doi: 10.23919/IPEC.2018.8507672.
- [94] J. Hu, M. Stieneker, P. Joebges, and R. W. De Doncker, "Intelligent DC-DC Converter Based Substations Enable Breakerless MVDC Grids," *Conf. Rec. 3rd IEEE Int. Work. Electron. Power Grid, eGrid 2018*, 2018, doi: 10.1109/eGRID.2018.8598689.
- [95] N. H. Baars, J. Everts, C. G. E. Wijnands, and E. A. Lomonova, "Performance Evaluation of a Three-Phase Dual Active Bridge DC-DC Converter with Different Transformer Winding Configurations," *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 6814–6823, 2016, doi: 10.1109/TPEL.2015.2506703.
- [96] J. Hu, S. Cui, S. Wang, and R. W. De Doncker, "Instantaneous Flux and Current Control for a Three-Phase Dual-Active Bridge DC-DC Converter," *IEEE Trans. Power Electron.*, vol. 35, no. 2, pp. 2184–2195, 2020, doi: 10.1109/TPEL.2019.2922299.
- [97] J. Hu, N. Soltan, and R. W. De Doncker, "Asymmetrical duty-cycle control of three-phase dual-active bridge converter for soft-switching range extension," *ECCE 2016 - IEEE Energy Convers. Congr. Expo. Proc.*, no. September, 2016, doi: 10.1109/ECCE.2016.7854888.
- [98] Y. J. and W. L. J. Huang, Y. Wang, Z. Li, "Simultaneous PWM control to operate the three-phase dual active bridge converter under soft switching in the whole load range," in *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2015, pp. 2885–2891, doi: 10.1109/APEC.2015.7104760.
- [99] and W. L. Zhuoqiang Li, Yue Wang, Ling Shi, Jun Huang, "Optimized modulation strategy for three-phase dual-active-bridge DC-DC converters to minimize RMS inductor current in the whole load range," in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, 2016, pp. 2787–2791, doi: 10.1109/IPEMC.2016.7512739.
- [100] and J. Z. J. Huang, Z. Li, L. Shi, Y. Wang, "Optimized Modulation and Dynamic Control of Three-Phase Dual Active Bridge Converter with Variable Duty Cycles," *IEEE Trans. Power Electron.* (, pp. 1–1. issn: 0885-8993, 2018, doi: 10.1109/TPEL.2018.2842021.
- [101] LEYBOLD, "DC Motor Supply 1 kW 725 862D." [Online]. Available: <https://www.leybold-shop.com/dc-motor-supply-1-kw-725862d.html>.
- [102] T. Technologies, "SiC/IGBT 3 Phase Inverter Development Kit." [Online]. Available: <https://www.taraztechnologies.com/product/power-electronics-modules/power/3-phase-inverter-development-kit/>.
- [103] E.-T. Electronics, "E65/32/27 N27 ferrite cores B66387G0000X127," 2013.

[Online]. Available: <https://www.digikey.com/en/products/detail/epcos-tdk-electronics/B66387G0000X127/3914876>.

[104] LEYBOLD, “Resistive load 0.3 LD732 40.” [Online]. Available: <https://www.leybold-shop.com/resistive-load-0-3-73240.html>.

[105] SoCan, “SCK3 Series Hall-Effect Open Loop Current Sensor.” [Online]. Available: https://szsocan.com/english.php/article/productinfo/product_id/304/action/cpgg.html.

Vitae

Name	:Hamed Mohammed Bin Qadhi
Nationality	:Yemen
Date of Birth	:6/23/1993
Email	:h.binqadhi@gmail.com
Address	: Seyion – Hadhramout – Yemen / Zip Code: 4720
Academic Background	B.Sc. in electrical Engineering (January 2018), from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia M.S. in electrical Engineering (May 2022), from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia
Papers under preparation	“Challenges and solutions of Protection in DC Microgrids: a review” “New Modulation and Fault control of Three-phase Dual Active Bridge DC-DC Converter”