ADVANCED CONTROL OF DUAL ACTIVE BRIDGE MULTILEVEL INVERTER WITH OPEN-WINDING TRANSFORMER MODEL

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AZUWIEN AIDA BINTI BOHARI

A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy in Electrical Engineering

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MAY 2021

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged

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Specially dedicated to my beloved parents, family, husband, and my lovely kids.
Mohd Nizam Bin Mohd Talib
&
Syafia Nurhanna Binti Mohd Nizam
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ABSTRACT

In recent years, Renewable Energy Sources (RES) are used to fulfil the growing demand for energy. The integration of RES into the grid incorporates power electronic converters for energy conversion. Voltage unbalance is one of the typical adverse grid disturbances commonly encountered in RES. Power quality (PQ) issues have turned out to be major problem and become extra prominent for users from all levels of usage as more nonlinear equipment are connected to the power grid. Using efficient energy conversion topologies by itself is inadequate in controlling system performance. In order to maintain and increase the system stability and reliability, Model Predictive Control (MPC) has been designed for Direct Power Control (DPC) namely Model Predictive Direct Power Control (MPDPC) which improves the PQ referral detection and reduces power ripple. Conservative Power Theory (CPT) has recently emerged to introduce new concepts concerning the definition of power and current terms. Consequently, this study proposed MPDPC of Dual Active Bridge Multilevel Inverter (DABMI) for grid connected application which incorporate the concept of CPT. The objectives of the proposed control approach is to improve the system performance during various conditions specifically for balanced and unbalanced grid voltage condition with two different cases of topology, namely DABMI and DABMI, with floating capacitor voltage. The ultimate goal of this study is to establish an advanced controller using MPDPC based CPT concept which improves steady state, transient state, Total Harmonic Distortion current (THDi) and lessens the power ripple. The complete DABMI along with the proposed MPDPC based CPT have been modeled in Matlab Simulink software and compared with the conventional and improved MPDPC. The simulation results show that the proposed approach manages to improve the system performance to achieve constant active and reactive power and at the same time produce the sinusoidal current under unbalanced testing condition with 0.56% of THDi for asymmetric DABMI topology and 1.12% of THDi for floating capacitor DABMI topology; those are below 5%, which is within the IEEE 519 standard.

ABSTRAK

Kebelakangan ini, Sumber Tenaga Boleh Diperbaharui (RES) digunakan untuk memenuhi permintaan tenaga yang semakin meningkat. Integrasi RES ke dalam grid menggabungkan penukar elektronik kuasa untuk penukaran tenaga. Ketidakseimbangan voltan adalah salah satu gangguan buruk grid yang biasa dihadapi di RES. Isu kualiti tenaga (PQ) ternyata menjadi masalah besar bagi pengguna dari semua tahap penggunaan dan menjadi lebih jelas kelihatan kerana lebih banyak peralatan nonlinear disambungkan ke grid kuasa. Penggunaan topologi penukar tenaga yang cekap tidak mencukupi dalam mengawal prestasi sistem. Untuk mengekalkan dan meningkatkan kestabilan dan kebolehpercayaan sistem, Model Kawalan Ramalan (MPC) telah direka untuk Kawalan Kuasa Secara Langsung (DPC) iaitu Model Predictive Direct Power Control (MPDPC) yang meningkatkan pengesanan rujukan PQ dan mengurangkan riak kuasa. Teori Kuasa Konservatif (CPT) baru-baru ini muncul untuk memperkenalkan konsep baru mengenai definisi kuasa dan istilah semasa. Oleh yang demikian, kajian ini mencadangkan MPDPC “Dual Active Bridge Multilevel Inverter” (DABMI) untuk aplikasi yang disambungkan ke grid yang menggabungkan konsep CPT. Objektif kaedah kawalan yang dicadangkan adalah untuk meningkatkan prestasi sistem dalam pelbagai keadaan terutamanya untuk keadaan voltan grid yang seimbang dan tidak seimbang dengan dua kes topologi yang berbeza, iaitu DABMI tidak simetri dan DABMI dengan voltan kapasitor terapung. Matlamat utama kajian ini adalah untuk mewujudkan pengawal lanjutan menggunakan konsep CPT berasaskan MPDPC yang meningkatkan keadaan ketika malar, keadaan sementara, Jumlah Herotan Harmonik arus (THDi) dan mengurangkan riak kuasa. DABMI yang lengkap bersama dengan CPT berdasarkan MPDPC yang dicadangkan telah dimodelkan dalam perisian Matlab Simulink software dan dibandingkan dengan MPDPC konvensional dan yang diperbaiki. Hasil simulasi menunjukkan bahawa pendekatan yang dicadangkan berjaya meningkatkan prestasi sistem untuk mencapai daya aktif dan reaktif berterusan dan pada masa yang sama menghasilkan arus sinusoidal dalam keadaan voltan tidak seimbang dengan 0.56% THDi untuk asimmetrik DABMI topologi dan 1.12% THDi untuk kapasitor voltan terapung DABMI topologi; berada di bawah 5%, yang mana dalam lingkungan piawaian IEEE 519.

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LIST OF SYMBOLS AND ABBREVIATION

$\alpha\beta$	Reference frame
AC	Alternating Current
APOC	Active Power Oscillation Compensation
CCS-MPC	Continuous Control Set Model Predictive Control
CMI	Cascaded Multilevel Inverter
CPT	Conservative Power Theory
DABMI	Dual Active Bridge Multilevel Inverter
DC	Direct Current
DCMI	Diode Clamp Multilevel Inverter
DPC	Direct Power Control
DS	Distribution System
DTC	Direct Torque Control
ESR	Equivalent Series Resistance
$e_{\alpha\beta}$	Grid voltages in $\alpha\beta$ reference frame
FCMI	Flying Capacitor Multilevel Inverter
FCS-MPC	Finite Control Set Model Predictive Control
FFT	Fast Fourier Transform
GPC	Generalized Predictive Control
g_{opt}	Optimal cost function

HBMI	H-Bridge Multilevel Inverter
i	Current
L	Inductor
MI	Multilevel Inverter
MPC	Model Predictive Control
MPDCC	Model Predictive Direct Current Control
MPDPC	Model Predictive Direct Power Control
NPC	Neutral Point Clamp
OSS-MPC	Optimal Switching Sequence Model Predictive Control
OSV-MPC	Optimal Switching Vector Model Predictive Control
OWT	Open Winding Transformer
p	Active Power
PI	Proportional Integral
PR	Proportional Resonant
PLL	Phase Lock Loop
PQ	Power Quality
PV	Photovoltaic
PWM	Pulse Width Modulation
q	Reactive Power
R	Resistor
RES	Renewable Energy Sources
RPOC	Reactive Power Oscillation Compensation
STATCOM	Static Compensator
THD	Total Harmonic Distortion

THDi	Total Harmonic Distortion Current
UPQC	Unidirectional Power Quality Conditioner
$u_{\alpha\beta}$	Inverter voltage in $\alpha\beta$ reference frame
V	Voltage
Vcap	Capacitor voltage
VOC	Voltage Oriented Control
ω_s	Grid frequency

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter provides the background of the research, hence focusing on the issue in grid connected application described in Sections 1.2 and 1.3. The objectives and scopes of this research are properly discussed in Sections 1.4 and 1.5. Research contribution and thesis outline are concisely explained in Sections 1.6 and 1.7, respectively.

1.2 Research Background

Following the significant increase in the penetration of intermittent renewable energy sources (RES) into the grid, innovation in power electronics has relentlessly been enhanced. Remarkable progress has involved improved controllers, topologies of the circuit, and semiconductor devices. The bulk source for meeting the energy demand is fossil fuels. Despite its efficiency, drawbacks of conventional energy source such as increased air pollution, depleting fossil energy source, and higher cost have made it important to look towards the RES as a future energy solution [1]. Developments in renewable energy integration are distinctly essential as need affordable, reliable, and clean energy.

A large amount of research effort has been made in order to diversify the primary energy sources and to accommodate the growth in consumption. This consumption growth, allied with the limited power generation capacity of traditional power plants, encourages the development of Distributed Generation (DG) systems. Figure 1 illustrates a simplified diagram of a grid-connected DG concept.

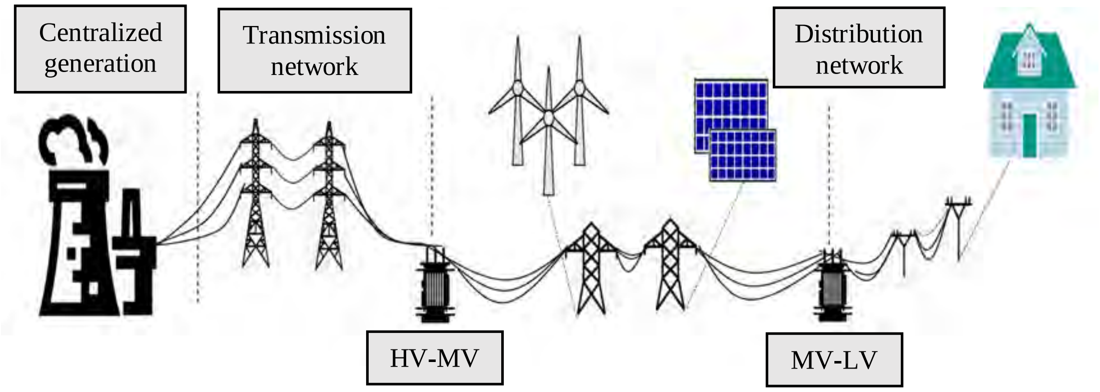


Figure 1.1: Simplified diagram of a grid-connected DG concept

The practice of having generation near to the consumption centers instead of the traditional large centralised power plants provides many advantages such as reduction of power losses in transmission and distribution lines, improvement in power quality, reduction of power usage, and improved reliability of the power supply. It is also less impacting on the environment. However, the DG systems are frequently connected to rural areas where weak grids are prominent. Consequently, noticeable voltage differences between different locations are to be expected and certain power quality issues can arise. Integration of the RES into the grid incorporates power electronic converters for the conversion of energy [2]. With the anticipated rise in the penetration of RES, a power system is required to accommodate some exceptional grid conditions commonly encountered in a weak grid system.

Electrical power quality (PQ) is a broad area dealing with issues that include power systems engineering, from transmission and distribution, to the end users. Approximately 70% to 80% of all related power quality problems can be attributed to faulty connections [3]. There are various categories of PQ issues namely power frequency disturbances, electromagnetic interference, transients, harmonics, and low power factor. Among these problems, harmonics is the most dominant. For these issues to be managed, electric utilities must comprehend the impact of voltage quality on the end user's equipment. Conventional power sources are inadequate to meet the expanding power demand, thus the power quality is decreased. Customised power gadgets like static compensator and unidirectional power quality conditioner are among interfacing devices between the grid and users to resolve voltage and current disturbances and enhance the power quality [4].

Better performance of future power systems is possible by using power electronic interfaces. Several control parameters involved are frequency, system voltage, harmonics, and active and reactive power. A proper power converter selection is important in order to function as a good interface between the grid and RES. Renewable energies, such as wind and photovoltaic energy, are particularly varying because of changes in climate [5]. This may bring about an abundant variety of voltage or frequency to the grid. Wide variations in the number of renewable energies' PQ would deteriorate the quality of the grid. The solution to this problem is to control the power electronic converter, synchronise it to the grid, thus efficiently maintaining the PQ of the system [6].

Therefore, the control of grid connected voltage source converter has attracted a lot of attention nowadays. Conventional control methods are commonly unsuccessful to evaluate the unbalanced grid voltage which regularly occurs in an isolated power grid that is distant from the main power system and is inclined towards unbalanced faults. These unbalanced operations cause fatigue to mechanical components due to non-sinusoidal output currents, power, and unequal power losses [7].

Generally, control methods can be broadly classified into direct and indirect control methods. Recently, advanced control technique has been studied for controlling power flow between renewable resources and grid directly, without multiple control loops as in the conventional linear controllers that are based on frequency response. Direct Power Control (DPC) is one of the most popular direct control strategies for grid connected inverter. This technique is derived from the concept of direct torque control (DTC) where in each sampling time, an optimal voltage vector is selected from look-up table in order to push the state of the system towards the reference value. The main drawback of the DPC strategy is that the use of a hysteresis controller has caused variable switching frequency and hence dispersed harmonic spectrum. In addition, it suffers from poor reference tracking with a large power ripple.

Model Predictive Control (MPC) has attracted significant attention from the power electronics community. In the field of academic control, MPC has become a significant research subject since the 1980s. Direct power control based MPC approach was established in order to overcome the drawbacks in DPC strategy [8]. In recent years, the MPC that has been designed for DPC improves reference tracking and reduces the power ripple. Flexibility, simplicity in the implementation, and improved efficacy in the output quality are several advantages of the MPC compared to the conventional controller. All these enhancements may be instantaneously reachable based on the design of the controller.

Different converter topologies have a great impact on system performance [9]. The multilevel inverter innovation has been generally perceived as a practical solution to prevent these power switching converters from reaching voltage limit. One of the advantages in utilising a multilevel inverter is its low Total Harmonic Distortion (THD) due to almost sinusoidal output voltage waveforms produced by multilevel inverter. Multilevel inverter has the ability to improve the output waveform, lessen the dv/dt stresses, lower the EMI effect, and increase the switching frequency that will produce lower switching losses [10, 11]. Therefore, low harmonics and power ripple are crucial in order to reduce costs due to power losses and poor functioning of equipment, both for the consumers and in the electrical distribution system. Hence, to improve the power quality issues, this work proposes an advanced control strategy for grid connected dual-active bridge multilevel inverter (DABMI) for grid connected application.

1.3 Problem Statement

Considering the importance of implementing intermittent RES into the utility grid, extensive work has been undertaken to design an effective control system for grid-connected power electronic inverters in addressing various adverse grid conditions. Voltage unbalance is one of the typical adverse grid disturbances commonly encountered in the RES. The fact that grid-tied inverter vulnerability leads to unbalanced grid voltage problems and experience severe power oscillation has taken the direction of the research into unchartered territory.

As for now, the real approach to the problem associated with critical power oscillation and non-sinusoidal current waveform has been limited to conventional current control strategy, wherein proportional-integral (PI) controllers [12, 13] and proportional-resonant (PR) controllers [14] are adopted in the rotating and stationary reference frames. These controllers have bottlenecks in achieving multiple control objectives, despite their complicated design with a cascaded structure. Conventional controllers have low dynamic response and demand a phase lock loop (PLL) to synchronize with the power grid [8]. To mitigate the impact attributed to the conventional controller, it is necessary to modify the table-based Direct Power Control (DPC) with the help of nonlinear hysteresis comparators [15-18].

Within the context of unbalanced network conditions, preliminary studies reported that the mainstream solution in Model Predictive Direct Power Control (MPDPC) could estimate new current references or new power references from the decomposition mechanism for positive- and negative-sequence grid components [19, 20]. The requirements of PLL, pulse-width modulation (PWM), or other complicated extraction techniques are mandatory in the decomposition process [21]. Even though sequence extraction techniques and PLL are not required in [22-24], power compensation strategy is mandatory to achieve sinusoidal current waveform, and, at the same time, the twice grid frequency oscillations that exist in active and reactive powers will be removed. However, this inevitably leads to computational complexity and substantial tuning work.

The unbalanced fault-ride through the controllers in existing literature that portrays the ability to deal with unbalanced grid circumstances reveals that the studies implement the same power concept. Instantaneous pq theory was introduced in [25] and is frequently adopted among the researchers. The controllers can achieve selective control targets during network unbalance, such as oscillation-free active power and oscillation-free reactive power and symmetrical and sinusoidal grid current [26]. Despite its promising performance, the nature of the instantaneous pq theory permits only one out of the three control targets to be fulfilled.

PQ issues have turned out to be an essential problem for power consumers at all levels of utilisation particularly during unbalanced and distorted grid voltage. This condition experience severe power oscillation and further lower the PQ that led to power losses and malfunction equipment. To reflect the novelty of this work, a new power theory, termed the conservative power theory (CPT), has recently emerged to present a new concept by which to define power and current terms [27]. This feature renders the CPT a strong candidate for selective compensation to improve the PQ in distributed generation systems, such as microgrids and smart grids [28-32]. The incorporation of CPT into MPC would bring this work into previously unexplored research area. The reason for advocating MPDPC, instead of Model Predictive Current control (MPCC) is to avoid the intense computational complexity incurred by the great number of mathematical operations in finding the decomposed current components of CPT [33].

The application of the novel CPT-based MPDPC scheme in the DABMI is tested in this work. This topology uses two active bridges to generate multilevel AC voltages [34]. The use of the transformer to provide voltage isolation improves voltage boosting capability, which further emboldens the usage of this topology for grid-connected renewable energy systems [35]. The proposed control approach is conceptually straightforward and entails only a minor modification to the conventional MPDPC. Unlike a conventional MPDPC, which employs the instantaneous pq theory, the suggested MPDPC achieves pure sinusoidal and symmetrical grid currents which effectively attenuates the power oscillations in the instantaneous active power and instantaneous reactive power during unbalanced grid voltage. This is done without the use of complicated power compensation techniques with lessened active and reactive power ripple and THDi.

1.4 Objectives

The aim of this research is to develop Advance Control of Dual Active Bridge Multilevel Inverter (DABMI) with Open Winding Transformer (OWT) for Grid Connected Application and the objectives of this research are:

1. To develop a mathematical model of DABMI for grid connected application.
2. To formulate an enhanced MPDPC for the grid connected DABMI.
3. To minimize the THDi and power ripples by enhancing the ancillary services in the grid connected DABMI.
4. To investigate and verify the performance of MPDPC based CPT concept through transient response and harmonics.

1.5 Scopes

This research focuses on:

The initial work of this research is carries out on the modeling of DABMI in grid connected application by generating suitable switching states of voltage vector. The proposed topology is being mathematically modeled and designed based on emerging predictive control method namely MPDPC.

The enhanced MPDPC for the grid connected DABMI, incorporated with instantaneous pq theory and CPT, are formulated by focusing on unbalanced grid voltage conditions. The mathematical proofs have been derived in order to clarify the difference between the two power theories.

In order to produce symmetrical and sinusoidal grid current along with minimizing the power ripple and THDi, power compensation technique must be adopted. The MPDPC of DABMI based instantaneous pq theory is improved by incorporating ancillary services, namely active power oscillation compensation (APOC) and reactive power oscillation compensation (RPOC) method.

The proposed MPDPC of DABMI based CPT is introduced by eliminating the complicated sequence extraction technique to achieve minimum THD within the IEEE standard. At the same time, it is able to achieve three particular control objectives which are producing sinusoidal and symmetrical grid current during unbalanced grid voltage without oscillation in active power (P) and reactive power (Q).

The proposed advanced control of DABMI with OWT for grid connected application is being implemented through Matlab/Simulink software using SimPowerSystem. The performance of the proposed system is investigated and the feasibility of the proposed system is compared against the conventional and improved MPDPC. The adopted system parameters for all control approaches are summarised in Table 1.1. The behaviour of the system is observed with the unbalanced grid voltage being obtained by increasing the magnitude of phase *a* grid phase voltage (*e*) by 10% and decreasing the magnitude of *e* for phase *b* by 10% for both asymmetric and floating capacitor DABMI topologies.

Table 1.1: Parameter of a tested power system

Parameter	Symbol	Value
Grid frequency	ω	$2\pi50$ rad/s
DC side voltage	V_{dc}	650V
Grid phase voltage	e	230V
Sampling period	Ts	50μs
Inductance	L	9mH
Equivalent series resistance	R	0.14Ω

1.6 Research Contribution

The contributions of this research work are:

(i) Modeling the MPDPC for grid connected DABMI based on instantaneous pq theory is crucial to further identify the characteristics, effect and behavior of the system performance which usually permits only one out of the three control targets during unequal grid voltage condition. Referring to the model, MPDPC analysis for grid connected DABMI can be implemented as a continuous study to justify the next issue under an unbalanced network condition.

(ii) The incorporation of CPT into MPDPC is a topic yet to be investigated. The proposed control approach entails only slight modification of the conventional MPDPC and the unbalanced fault tolerant ability is enhanced without any additional cost. The proposed control approach is able to achieve all of three control targets, reduce the THDi and lessen the power ripple.

(iii) An enhanced technique of MPDPC based CPT can then be extended to the establishment of MPDPC for grid connected DABMI with floating bridge capacitor. The overall control structure is kept simple wherever complicated sequence extraction of grid component is encountered. The proposed control approached managed to accomplish constant active and reactive power without compromising on performance such as transient response and THDi.

1.7 Thesis Outline

This thesis consists of 5 chapters. The first chapter gives some background and introduction of the research. Problems which existed in previous works are highlighted and research objectives along with research scopes are also discussed here.

The second chapter of this report focuses on studying previous works or research which are related to the scope of this project. The existing topology and the control strategy based MPDPC are being taken as references in order to implement the topology of DABMI which integrates with MPDPC. The concept of instantaneous pq theory and the CPT are also explained.

The third chapter of this report describes the methodology of the project implementation for DABMI control based MPDPC. Special emphasis is also placed on deriving mathematical proof to justify the selective power oscillation elimination in instantaneous pq theory and the simultaneous power oscillation elimination during balanced and unbalanced grid voltage condition. The circuit operation and space vector used in this project are also explained in this chapter for both cases of asymmetric and floating capacitor voltage control of DABMI.

The design and feasibility of the proposed MPDPC control strategy under balanced and unbalanced operating conditions are verified by simulation results in MATLAB/Simulink in Chapter 4 and proofs showing that the proposed approach can produce lower current harmonics and reduce power ripple.

Finally, Chapter 5 sets out the conclusion and future recommendations for improvement of this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents an overview of advanced control of DABMI with OWT for grid connected application. The fundamentals of Multilevel Inverter (MI) is first described. Then, the fundamental advanced control approach is explained. Background studies of the available control methods that have been implemented in MI are further discussed. Review of previous works on various types of advanced control methods for multilevel inverter, as well as their advantages and disadvantages, are also presented.

2.2 Multilevel Voltage Sources Inverter

Inverter is a power electronic equipment or circuitry which converts direct current (DC) into alternating current (AC) by using several control switches at anticipated output frequency and voltage. To convert DC to AC voltage, the inverter usually generates two different levels of output voltage and the inverter is known as two-level inverter. Although the two-level inverter is capable of generating AC from DC voltage, this converter cannot be used in high voltage and power application due to high frequency switching, losses, and stresses. High THD is also a major problem which makes it a challenging task to collaborate between the power electronic switches straight to the voltage grid.

One approach to eliminate the switching losses is by developing a multilevel inverter which is an inverter that produces a high number of switching states. By having additional switching states, the output voltage of the inverter can be stepped in small augmentations. This allows reduction of harmonics at low switching frequencies and along this line, decreases the switching losses. Lower *dv/dt* can be produced by the smaller voltage steps. This is the main reason why MI topology has been chosen. Figure 2.1 presents the classification of MI in the voltage source inverter.

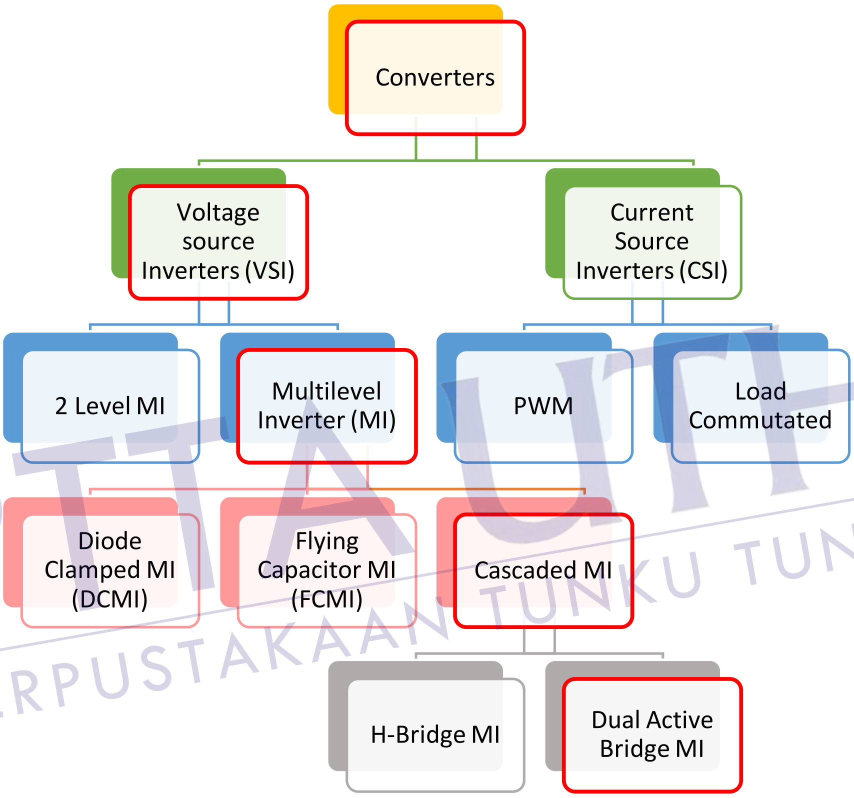
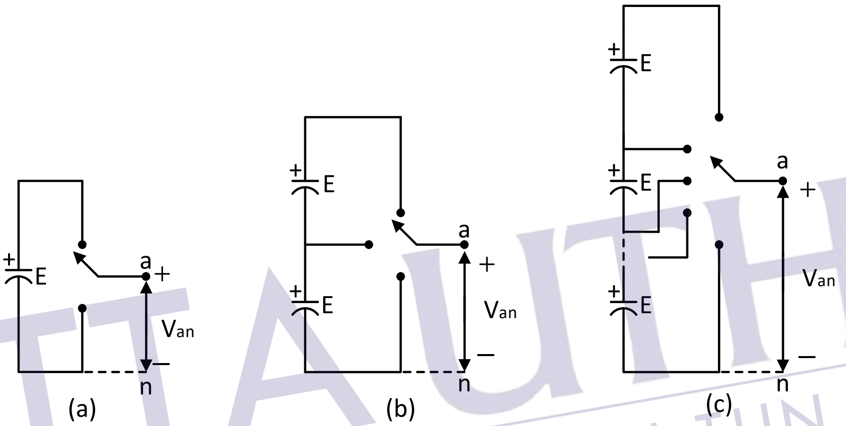


Figure 2.1: Classification of multilevel inverter

Over the last two decades, multi-level converters have gained significant recognition in the electrical and electronic drives industry. Some benefits of two-level converters are also provided by multilevel converters. Multilevel topologies are particularly prevalent in medium voltage applications. The necessary blocking voltage of each switch is decreased as opposed to the two-level converter which permits greater DC link voltage and removes the necessity for linked series switches. Low voltage consumption on one switch causes lower *dv/dt* and causes the level of electromagnetic interference to decrease. Increasing the voltage resolution makes it possible to reduce the device's switching losses and switching frequency. On the other hand, THD of the output waveform generated by switching frequency device is also reduced.

The MI topology was initially presented with three levels inverter at the start of the year 1975. High level output voltage with high power rating that lowers the device’s rating can be generated in MI. As several lower level DC voltages are the input, the desired alternating voltage level can be produced using MI. Various types of DC voltage sources can be used as the input such as renewable energy system, capacitor, and battery. Figure 2.2 shows a generalised form of a two-level in (a), three-level in (b), and n level converter in (c).



(a) (b) (c)

Figure 2.2: Phase leg of inverter [36]

With a specific end goal to use the energy from RES, control transformation framework is fundamental. In order to introduce the utility power supply into the grid, inverter is the last component involved. Inverters have played a prominent role in the modern technological world upon the sudden rise in renewable energy (RE) technologies. To create a more environmental friendly power generation, RES have been incorporated into the utility grid on a large scale [37]. In recent years, MI topologies are widely utilised as a part of a renewable energy system because of the lower THD posed by MI. By expanding the number of levels in the inverter, the output voltages have more steps in producing the waveform, which gives better approximation of the sine wave, reducing the instantaneous error and decreasing the value of THD [38]. Considering the developing utilisation of high power inverter, MI has drawn increased interest from the scholarly community and industry in the current decade.

The term multilevel began with the three-level inverter presented by [36]. The explanation behind the expanded intrigue is that the multilevel inverters are practical innovations that can be applied in high-power applications. MI can produce waveform of output voltage that has a greater number of steps. MI topologies are comprehensively arranged into three types namely Diode Clamped Multilevel Inverter (DCMI) also known as Neutral Point Clamped multilevel inverter (NPCMI), Flying Capacitor Multilevel Inverter (FCMI) also called Capacitor Clamped Multilevel Inverter (CCMI) and lastly, the Cascaded Multilevel Inverter (CMI) [39].

2.2.1 Diode Clamped Multilevel Inverter (DCMI)

In 1981, the earliest type of MI was the DCMI also commonly called the 3 level NPC, has been originally proposed by Nabae et al. [40]. The DCMI comprises a series of capacitor that offers various voltage levels as the output of the inverter. By adding the quantity of the capacitors, the topology of the DCMI can be expanded, as shown in Figure 2.3.

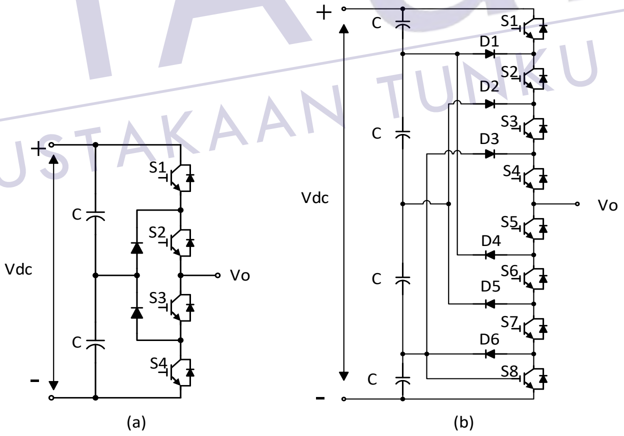


Figure 2.3: Three levels (a) and five levels (b) of DCMI [36]

The multilevel output voltage is produced when the switching state is performed, which is when one of the inverter output terminals is linked to the neutral point through one of the clamping diodes. DC bus capacitor at the DC side of inverter will be separated into two. Clamping diodes are the diodes that are connected to the neutral point. Input voltage across all the capacitors in a 5 level DCMI then receive a voltage of $V_{dc}/4$ for each capacitor.

If S_1 to S_4 are switched on, $3V_{dc}/4$ is blocked by D_1, $V_{dc}/2$ is then being stopped by D_3 and D_4 that block the voltage of $V_{dc}/4$ in order to produce the positive output voltage of $V_{dc}/2$. The output voltage of $V_{dc}/4$ is produced by switching on S_2 to S_5. The output voltage of 0 is then obtained when S_3 to S_6 are switched on. By inverting the switching states of the positive output voltage, the negative output voltage of $-V_{dc}/2$ and $– V_{dc}/4$ are further generated [41].

Uneven distribution loss between the switching devices and complexity in design are major concerns in the DCMI topology posing as the major drawbacks in DCMI topology. Fluctuating DC-link capacitor voltage then occurs if 0, $V_{dc}/4$ and $-V_{dc}/2$ are matched to the output voltage. As a result, DCMI needs a neutral point balancing technique to reduce imbalance of capacitor voltage. However, this technique becomes more complicated particularly when passive front end supplies to the DC-link [42].

The maximum use of the switching devices may lead to disaster. Another problem that exists in DCMI is the DC level is next be discharged if the monitoring is not accurate. When the level of output voltage is increased, it is prone to higher clamping diodes. The four level DCMI has become another option instead of three level and five level DCMI but still, this topology experiences a similar issue with three level and five level DCMI [43]. Because of these factors, in practical application, DCMI is usually limited to three levels of output voltages.

2.2.2 Flying Capacitor Multilevel Inverter (FCMI)

The structure of the Flying Capacitor Multilevel Inverter (FCMI) in Figure 2.4 is very similar to DCMI, however this topology uses series connection of flying capacitor in place of diode to limit the voltage and separate the input of DC voltages. Unlike diode in DCMI, the capacitors here are unable to block the reverse voltage in this topology. The voltage output produced in FCMI is just half of the DC input voltage and the switching states in DCMI are similar to the FCMI topology.

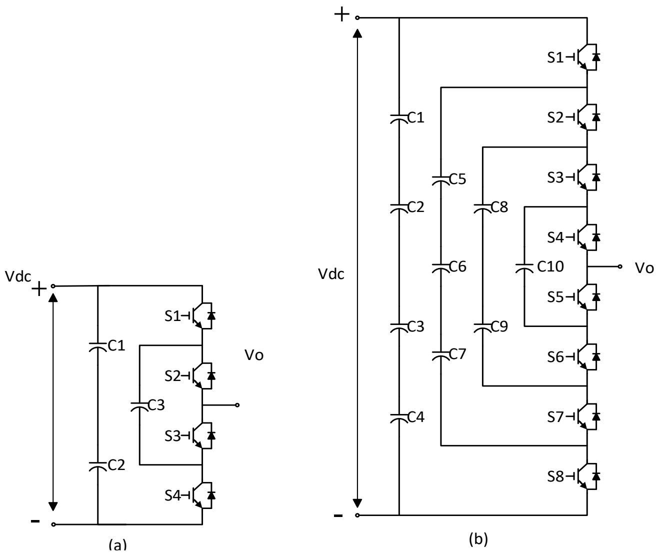


Figure 2.4: Three level (a) and five level (b) FCMI [44]

Additional flying capacitor is able to lead as additional voltage level in FCMI. Total voltages of $3V_{dc}/4$ in five level FCMI are obtained by charging the clamping capacitor of C_5 to C_7, $V_{dc}/2$ output voltage are gained by charging C_8 and C_9 while $V_{dc}/4$ are produced by charging the capacitor C_{10}. The negative output voltage is generated by inverting the switching state of the positive output voltage. It is important to choose the switching combinations for the five level FCMI so that the voltages across the clamping capacitors are retained at the desired level. As the voltage level expands, the difficulty of the capacitor voltage balancing often increases. Similar with DCMI, if the voltage level is getting bigger, the topology of FCMI becomes inefficient.

2.2.3 Cascaded Multilevel Inverter (CMI)

Among the three MI, the DCMI and FCMI use higher number of power switches than the CMI. Thus, CMI topology is more popular for grid connected Photovoltaic (PV) applications [45]. However, due to a considerably large number of power switches and related switching and conduction losses, the efficiency of the CMI is still low and the cost is still high. There are two types of cascaded MI, namely cascaded H-bridge multilevel inverter (HBMI) and dual two-level inverter also known as DABMI.

2.2.3.1 H-bridge Multilevel Inverter (HBMI)

The arrangement couples of switches and capacitors forming H-bridge and different cells in H-bridge have isolated voltage sources. To generate sinusoidal voltage output in HBMI, HBMI must be connected in series. The amount of voltage produced by each cell is the output voltage of the inverter. The main drawback of this topology is that each cell needs its own input DC voltage which makes the system expensive, further increasing the losses, and the weight of the system. HBMI topology and the relationship between switching states and the output voltage are shown in Figure 2.5.

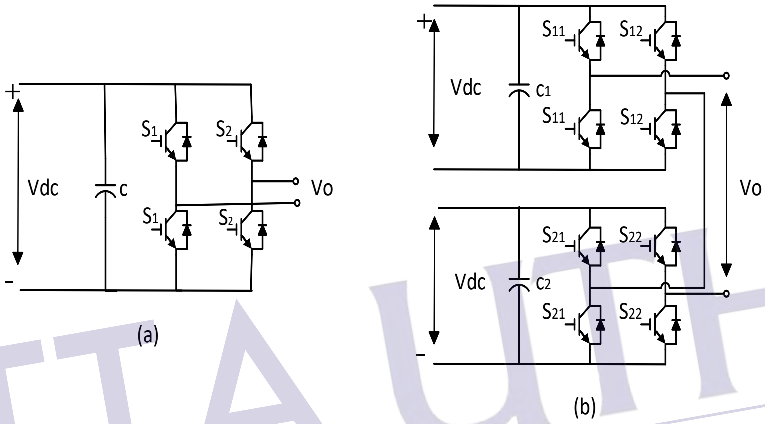


Figure 2.5: Three level (a) and five level (b) of H-bridge MI [46]

The flexibility of expanding the amount of output voltage level is one of the greatest benefits provided by the HBMI topology. In comparison, the HBMI is able to produce output voltages with double the magnitude of the topologies of FCMI and DCMI for a defined DC-link voltage. Compared to the topologies of DCMI and FCMI, the topology of the HBMI has a smaller number of total components. The HBMI drawback is the necessity to separate the DC-link voltages for every cell. A transformer with several isolated secondary winding is used in this topology to provide these voltages, but as a result, the system complexity is increased.

2.2.3.2 Dual Active Bridge Multilevel Inverter (DABMI)

Among the cascade converters, the DABMI topology as shown in Figure 2.5 has received attention due to the simplicity of the power stage and the arrangement's fault-tolerant capacity. Furthermore, DABMI is more reliable because the output of the inverter can be short-circuited when one of the inverters fails. DABMI can then function as a standard two level three-phase inverter [47]. Two isolated DC sources are used for the DABMI in order to cut the path of common-mode current flow and to achieve multilevel voltage waveforms [48].

This is the reason why dual two-level inverter has been chosen in this project. DABMI uses two six-transistors that allows the inverter to imitate and produce voltage similar to waveforms generated by three-level and four-level three-phase inverter [49, 50]. The industry has proved that two-level inverter is the basic building block. This becomes one of the reasons why DABMI is very convenient to use rather than other multilevel inverters. The DABMI does not require fast recovery clamping diodes and is unaffected by neutral point fluctuations experienced in the NPCMI configuration.

FCMI topology uses more capacitors than DABMI [51], fewer isolated DC supply than H-bridge converters [52, 53] and less diodes than DCMI [54]. For instance, in a three-phase three-level inverter, FCMI needs extra capacitor control, HBMI demands two more isolated supplies, and DCMI requires six additional diodes. Furthermore, when the output voltage level increases in FCMI and DCMI, it becomes more difficult for the capacitor to balance the voltage. Moreover, the topology of DABMI can produce different output levels which are two-level, three-level, and four-level inverters based on the possible switching state and active vector produced by the MI. This is the main reason DABMI has been adopted in this work.

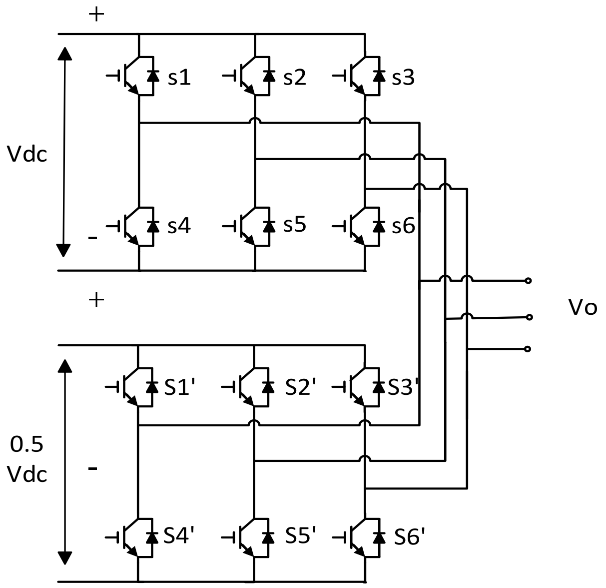


Figure 2.6: Dual Active Bridge Multilevel Inverter (DABMI) [55]

2.2.3.3 Symmetric and Asymmetric Multilevel Inverters Topologies

There are two latest topologies in cascaded MI, which are symmetric and asymmetric multilevel inverter [56]. Both topologies have their advantages and disadvantages that have been considered by numerous researchers. In order to reduce the THD, high output voltage should be generated [57]. Generally, for conventional multilevel inverter, the number of switching devices increases with the increase of inverter voltage level. The common advantage of asymmetric topology is that it is able to generate a high level of output voltage using the same symmetric structure. However, the value of voltage sources is different where first V_{dc} source is equal to V_{dc} and second V_{dc} source is equivalent to $2*V_{dc}$, while the value of input Vdc in symmetric topology is equal to $V_{dc}1$. Basically, by increasing the level of the output voltage, a good quality sinusoidal waveform can be produced.

2.3 Model Predictive Direct Power Control (MPDPC) Approach

Various control algorithms have been introduced on MI to achieve high performance power control. The conventional controllers include the category of controllers for adding or subtracting a proportion and adjusting the system accordingly. This controller is considered as the most fundamental controller in the industry for controlling linear systems, and regarded as the base of control theory. Meanwhile for the advanced controller, during various adverse grid conditions such as unbalanced and distorted grid voltage condition, a number of problems can occur in the system. In order to overcome this situation, a suitable controller must be designed and MPDPC is chosen as the proposed control approach.

2.3.1 Model Predictive Control

Among the various types of advanced control methods, MPC is one of the best controllers that has been effectively used in industrial applications [58, 59]. Despite the fact that the idea of MPC was from the 1960s as an application of optimal control theory, industrial enthusiasm for these ideas began in the late 1970s [60]. From that point onwards, MPC has been successfully employed in the substance procedure industry, where time constants are sufficiently long to perform all the required computations. Early application of MPC in power electronics began in the 1980s in considering high-power system with low switching frequencies. The utilization of higher switching frequencies was unrealistic at the time because of the large computation time required for the control algorithm. Figure 2.7 illustrates the basic control diagram in MPC.

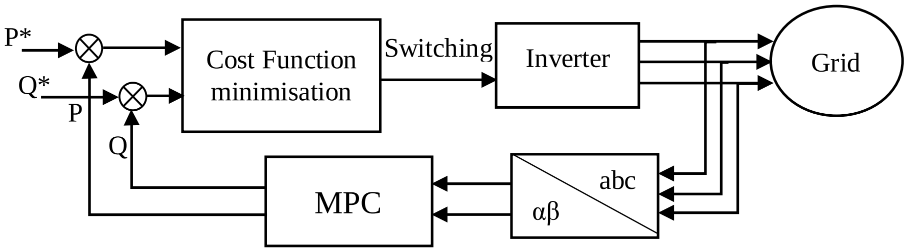


Figure 2.7: Basic control diagram in MPC

However, with the development of fast and powerful microprocessors, interest in the application of MPC in power electronics has considerably increased over the last decade. MPC describes a wide family of controllers, not a specific control strategy. The common elements in this kind of controller includes using a model of the system to predict the future behavior of the variables until a time of predefined horizon, and selection of the optimal actuations by minimizing a cost function.

MPC strategies have been categorised into two, namely continuous control set MPC (CCS-MPC) where the switching state is produced by a modulator from the output of predictive controller, and finite control set MPC (FSC-MPC) which is based on discrete model. The latter uses the benefit of finite number of switching states in order to deal with the optimisation problem without using modulation unit and this has become its main advantage [61, 62]. Figure 2.7 presents the classification of MPC strategies applied to power converters and drives.

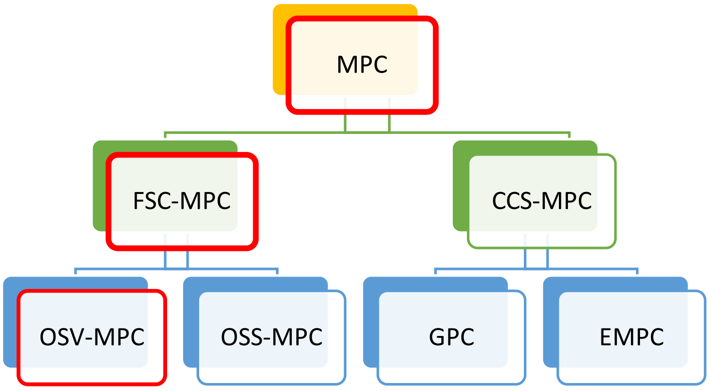


Figure 2.8: Classification of MPC strategies applied to converters and drives

The favourable strategies for power electronic applications in CCS-MPC are generalised predictive control (GPC) and explicit MPC (EMPC). GPC is beneficial for unconstrained and linear problems. EMPC permits the cooperation with the nonlinear and constrained systems. Complicated MPC formula is a major problem in GPC and EMPC in the power converters. FCS-MPC can be classified into two categories namely optimal switching vector MPC (OSV-MPC) and optimal switching sequence MPC (OSS-MPC).

The quantity of vectors applied in every sampling period is the major contrast between OSV-MPC and OSS-MPC. In order to solve the optimisation problem of OSS-MPC during per switching period, a restricted number of possible switching states is imposed by the control set. Using the OSS-MPC method, it causes the controller to take more time to make a decision [63]. The most common strategy of FSC-MPC in the application of power electronic is OSV-MPC. It uses the possible output voltage vectors of the power converter as the control set. Analyses prediction in OSV- MPC diminishes the optimal problem to a computed search algorithm and makes the algorithm very practical. Less computational burden is produced by OSV-MPC that allows for a reduction of the sampling time T_s as long as the switching losses are not affected.

MPC method depends on the way that only a finite number of possible switching states can be produced by MI and by using the topology of DABMI, behavior of the variables for every switching states can be predicted. Selected criteria for better selection of applied switching states must be determined using OSV-MPC. The criteria that should be included such as cost function is used to estimate the predicted values of control variables. Selection of minimum cost function is based on the variable calculation of predicted future value for every possible switching states. Modulation in this control technique is unnecessary because only one switching state is considered in every sampling interval that features distributed current spectrum [64].

The cost function is a description of the command goals that are typically connected to the parameters accompanying the references. Therefore, the error's quadratic value, is usually used to find the cost function's minimal value. If two or more goals need to be simultaneously accomplished, it can be merged as an amount of error terms. If these parameters are of the same type, such as the direct and quadrature components of the active power, reactive power and current, they can be directly added. But, if the variables are of different types, such as magnetic flux and torque, or voltages and currents, they must be added with standardization [65].

To select the minimum cost function, all possible states are evaluated and the optimal value is retained to be used in the next evaluation for determining the switching states. Cost function must be used with weighting factor, so that different control variables such as units and magnitudes can be changed to handle the value of each term. Compared to a three-phase two-level inverter, a decrease in the amount of calculation occurs when different optimisation strategy is used. The number of calculations is proportionate with the number of possible switching states produced in the system.

2.3.2 Direct Power Control (DPC)

Generally, there are a variety of control techniques for controlling power flow in voltage sources converter. The most common techniques are voltage-oriented control (VOC) and direct power control. The VOC uses internal current control loop to indirectly control the active and reactive power while DPC extinguishes the employment of current control in this strategy, thus offering easy implementation. With regards to the control methods during unbalanced grid voltage, with recent advances of MI, this motivates the need for an alternative approach: a conventional vector-oriented control strategy having a low performance because of the complexity in decoupling and transformation [66].

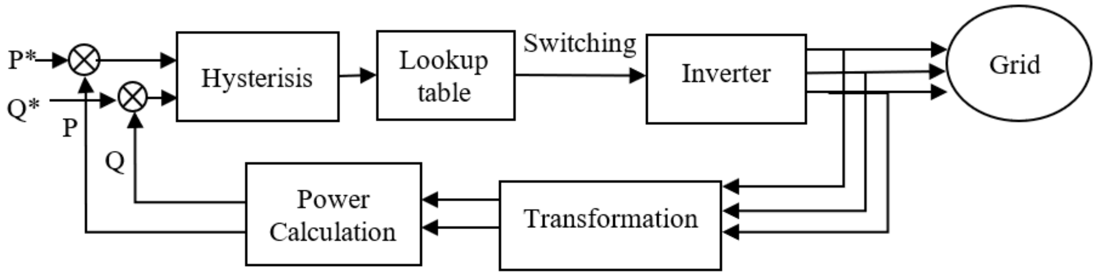


Figure 2.9: Basic control diagram in DPC

The DPC has become a popular strategy for grid connected converters. Nowadays, one line of research dominates the literature which put DPC as an effective control technique. This method, developed based on the fundamentals of DTC technique, is established by the instantaneous pq theory [67]. It involves producing the value of power reference when the error is computed from instantaneous active and reactive power which remain in the range of a fixed hysteresis band. Selected space vector that responds to the power variation is applied in conventional DPC that makes up for the lookup table.

Low power quality is apparent in conventional DPC which contains high ripple, higher total harmonic distortion, and complex design of harmonic [68]. Poor performance is imminent when low switching frequency is introduced into the system. Several modified DPC strategies focus on constant switching frequency instead of variable switching frequency; however, adoption of PWM modulators causes difficulties in coordinating transformation [17]. A variety of techniques, namely the MPC [66, 69] have been approached to improve the performance of the system in comparison with the conventional technique, allowing the control scheme to become simpler and more flexible [70, 71]. The DPC is a kind of high performance control strategy for the PWM converter; however, the switching table in conventional DPC is obtained in a heuristic way, which cannot ensure the effectiveness of the selected voltage vector [72].

Zhang, Qu, and Gao [73] proposed an innovative DPC that is supported during non-ideal grid voltage condition based on new description of reactive power. Switching table used is appropriate for simultaneous regulation of active power and reactive power, where the flexibility and reliability of former table-based DPC is totally retained. Unlike the recent DPC approaches to deal with unequal grid voltage, there is no need to extract positive and negative sequence current and complex power compensation calculation. The method of maximising the service ratio is often applied to further improve the performance of constant-state, built on the idea of reducing control errors.

In a separate work, a versatile strategy of grid connection which depends on the DPC is implemented under unbalanced grid condition, as introduced by Shen and Nian [74]. To remove harmonics in the current, two control variables which focus on VSI's mathematical formula are fixed. The Multiple Complex Coefficient Filter (MCCF) is implemented in the control scheme to extract the sequence grid current and voltage which are greatly important in calculating power compensations in order to apply the flexible approach between ripples of output power and non-ideal grid condition.

Different meanings of active power is introduced by Kahia et al. [75], focusing on extended pq theory which solves the problems happening in the former DPC. Decomposition of positive and negative sequence current or voltage component and power compensation technique are unnecessary. Therefore, a DPC technique focused on the switching table is built, focusing on the new concept of active power and former meaning of reactive power. Low THD, sinusoidal grid current, and constant active and reactive power can be obtained by the user of related switching table.

Shuning Gao et al. [76] currently developed advanced control techniques offering many benefits such as robustness to various conditions, non-dependence on synchronisation unit, and easier structure. The extraction of negative and positive sequence current component is developed using grid voltage modulated DPC controller in order to endure the power ripples during non-ideal grid voltage condition.

2.3.3 Model Predictive Direct Power Control

The MPC algorithm features fast dynamic response, robustness, and ease of implementation in power electronic converter. To date, the control approach for DABMI is generally limited to frequency response based on linear controller such as Proportional Integral (PI) controller [72,39] with different modulation stages. The concept of MPC can easily be integrated into the current control or direct power control to constitute the so-called model predictive current control (MPDCC) [19] or MPDPC [77, 78].

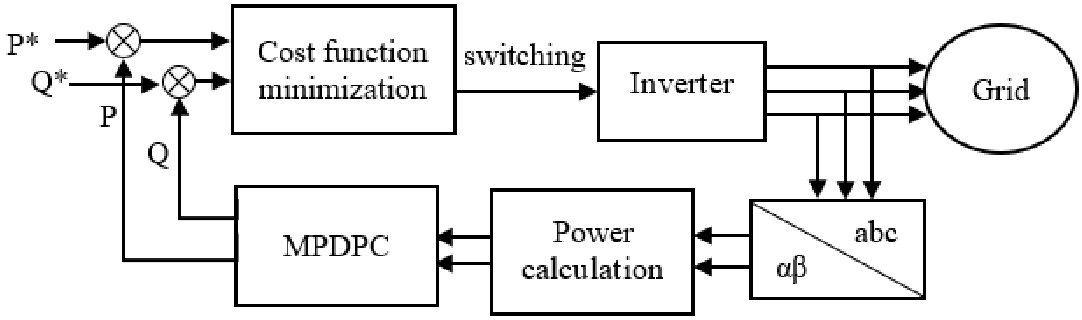


Figure 2.10: Basic control diagram in MPDPC

Various studies have proposed a clarification by calculating the new active and reactive power references for positive and negative sequence of the grid components, which focuses on unbalanced grid voltage conditions using MPDPC [77]. MPDPC is actually an extension of DPC where the active and reactive powers from the converter are directly controlled. The appropriate voltage vector is selected according to an optimisation cost function; hence, the instantaneous active and reactive powers are regulated directly in the stator stationary reference frame without the requirement of coordinate transformation, PI regulators, switching table, or PWM modulators. Rotary coordinate transformation and internal current control loop are unnecessary in MPDPC. This makes MPDPC simpler and efficient to achieve robust performance for the grid connected application. Nowadays, there are many attempts made in the direction of MPDPC where significant research has been using the control approaches in several converter topologies for grid connected application such as DCMI and FCMI [79].

One of the biggest challenges in making the converter operate in normal mode is the unbalanced grid voltage conditions. However, only a handful of them are discussed in this topic. Handling the problem lies in the non-ideal grid condition, where a new control method has been proposed in [80-82]. In the new control method, the positive and negative sequence current are controlled separately which results in low stability of the system and reduction of the transient response. There are only several studies that have investigated the performance of MPDPC for DABMI during non-ideal grid condition. Previously, problems in a weak grid i.e. unbalanced operating condition in voltage source inverter are resolved using the famous instantaneous pq Theory that was first adopted by Akagi et al. [25]. The results of these sinusoidal grid current and constant active and reactive power, can be accomplished by the pq theory [26]. However, the environment of Akagi's proposed method only allows one solution out of three objectives to be achieved with an additional compensation technique [20, 23, 83]. To achieve three selective control targets, power compensation methods are added into the system to achieve sinusoidal and symmetrical grid current, removing active power ripples, and cancelling reactive power ripples.

The most basic and fundamental requirement for MI with grid connected applications is to keep the inverter synchronised with the grid. The MI can provide suitable value for power despite grid voltage having varying frequency, amplitude, and phase. Synchronisation unit has been acknowledged to be a compulsory part for grid connected converter [84]. Power and reactive power can directly be controlled by using the MPC and this present technique has been promising in providing the

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