Model predictive control based D-STATCOM using three-level simplified neutral point clamped inverter

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**Model Predictive Control Based D-STATCOM
Using Three-Level Simplified Neutral Point
Clamped Inverter**

**LI WEIYI
SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING
2021**

Model Predictive Control Based D-STATCOM Using Three-Level Simplified Neutral Point Clamped Inverter

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Master of Engineering

July 14 2021

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarized materials, and has not been submitted for a higher degree to any other University or Institution.

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Authorship Attribution Statement

This thesis **does not** contain any materials from papers published in peer-reviewed journals or from papers accepted at conferences in which I am listed as an author.

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Acronyms

power quality	PQ
distribution static synchronous compensator	D-STATCOM
distributed generation	DG
three-level simplified neutral point clamped inverter	3L-SNPC inverter
model predictive control	MPC
distributed energy storage system	EDSS
static var compensator	SVC
static synchronous compensator	STATCOM
static var generator	SVG
three-level neutral point clamped inverter	3L-NPC inverter
tow-level	2L
synchronous reference frame	SRF
instantaneous reactive power	IRP
phase-locked loop	PLL
low pass filter	LPF
hysteresis current control	HCC
pulse width modulated	PWM
control-hardware-in-the-loop	CHIL
fast Fourier transform	FFT
total harmonic distortion	THD
hardware-in-loop	HIL

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Abstract

In the modern distributed generation-based system, the power electronic interfacing gives rise to some of the power quality (PQ) problems, such as the load voltage issues and harmonics. These PQ problems will pollute the power distribution system. To maintain acceptable power quality in modern power systems, reactive power compensation is receiving more and more attention. A distribution static synchronous compensator (D-STATCOM) is a compensator which is used to control the flow of reactive power in the distribution system. In this project, the D-STATCOM is utilized to compensate the reactive power in the microgrids. A three-level simplified neutral point clamped inverter is introduced. It comprises a front-end dual buck converter and a conventional two-level inverter. The dual buck converter can provide full, half and zero dc-link voltages. Compared with the conventional inverter, the three-level simplified neutral point clamped inverter can provide a better compensating performance. The three-level simplified neutral point clamped inverter is integrated with the D-STATCOM to achieve a better reactive power compensation effect, while further reducing the harmonics of the current on the source side. The mathematical model of the system is formulated and the model predictive control-based method is implemented for the system. The developed system is verified in the MATLAB/SIMULINK platform and simulated in OPAL-RT using dSPACE as the controller.

***Index Terms*—distribution static synchronous compensator (D-STATCOM); model predictive control; distributed generation; three-level simplified neutral point clamped inverter; reactive power compensation.**

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Chapter 1 Introduction

1.1 Motivation

In a modern distributed generation (DG) based microgrid system, the loads such as motors and pumps and generators such as wind turbines and solar PV systems are located in proximity. And the power electronic interfaces towards DG gives rise to some of the power quality (PQ) problems, which include load voltage issues, reactive power compensation and harmonics. These PQ issues can cause many problems to the power distribution system. Among them, reactive power compensation and harmonic control are becoming challenging tasks to maintain an acceptable degree of PQ in the modern power system [1].

Distribution Static Synchronous Compensator (D-STATCOM) is a compensating device which is generally used to compensate the flow of reactive power in the distribution systems, and it also has the function of controlling harmonics in microgrids [2]. The structure of the circuit has a great influence on the compensation effect of D-STATCOM, especially accuracy. The control method of D-STATCOM also has a great influence on the compensation effect and the response speed.

A three-level simplified neutral point clamped (3L-SNPC) inverter is originally used with gate turn-off thyristors. However, GTOs have been substituted with IGBTs since decades. This inverter comprises a front-end dual buck converter and a conventional two-level inverter. The dual buck converter can provide full, half and zero dc-link voltages [3] [4]. Combined with model predictive control (MPC) method, the use of this 3L-SNPC can make the output current of the D-STATCOM more accurate, thereby achieving a better compensation effect and reducing the harmonics in power grid.

Compared with MPC, the traditional hysteresis band control has some shortcomings. Firstly, the frequency of switching signals generated by the hysteresis control method is not constant and varies greatly, which will bring new harmonic pollution to the system. Secondly, the D-STATCOM based on hysteresis band control needs to compensate for some losses by using a proportional-integral controller, such as losses in the reactor, losses of switch devices and losses of the dc bus capacitor. And MPC also has better performance than hysteresis control in terms of response speed [5] [6]. Fig 1.1 shows the flow diagram of a general MPC. Taking these factors into consideration, the MPC based D-STATCOM can obtain a better compensation effect.

Fig 1.1 Flow diagram of general MPC

1.2 Objectives

The purpose of this thesis is to develop an MPC based D-STATCOM using the 3L-SNPC inverter for the reactive power compensation and harmonic control in the integrated system. The mathematical model of the integrated system will be formulated. The simulation model of the system will be built on the MATLAB/Simulink platform for experiment. Through this MPC based D-STATCOM using the 3L-SNPC inverter, the current waveform and harmonics of the system will be analyzed to verify the function of D-STATCOM. It is of great significance for improving the performance of D-STATCOM, as well as reducing the harmonics in DG in microgrids.

1.3 Major Contribution of the Thesis

Based on literature review, this thesis summarizes the structure and characteristics of the DG systems in microgrids. Considering the problems of the DG systems, this thesis focuses on reactive power compensation and harmonic control, and summarizes the types and development of reactive power compensators, by focusing on the structure, function and application advantages of D-STATCOM.

There are two factors that determine the performance of D-STATCOM: the circuit structure of D-STATCOM and the control method of D-STATCOM. Aiming at the structural design of D-STATCOM, this thesis compares traditional two-level (2L) inverters with three-level (3L) inverters. Obviously, 3L inverters can achieve better reactive power compensation and harmonic control effects. The types and structures of 3L inverters are also diverse. This thesis summarizes the common 3L inverters and designs a 3L-SNPC inverter. Considering the control method of D-STATCOM, this thesis analyzes the characteristics of traditional hysteresis current control (HCC) and MPC. In view of the advantages of MPC, this thesis implements D-STATCOM based on the MPC method.

Reactive power compensation and harmonic control are inseparable from the calculation of reference current. This thesis also analyzes several common calculation methods, and the instantaneous reactive power (IRP) method is chosen to apply to this project.

In this thesis, the mathematical model and simulation model of the system are established, analyzed, and tested in Simulink/MATLAB. Real-time simulation on OPAL-RT and experiment using dSPACE as a controller are carried out to further test the application ability of this system in practice.

1.4 Organization of the Thesis

In this thesis, the background of the proposed MPC based 3L-SNPC inverter is studied. According to the study and research of background knowledge, the theoretical model, mathematical model and circuit structure are proposed. Based on the circuit structure, the model is verified by simulation experiments. Finally, based on the experimental results, the effect of the MPC based 3L-SNPC inverter is summarized.

In the following chapters, firstly the concept of the DG systems and microgrids, the circuit structure of D-STATCOM and some calculation methods of the reference current will be reviewed. They are the basis of this project. The circuit structure of 3L-SNPC inverter and the principle of MPC, as well as their implementation will be reviewed in Chapter 2. Then the mathematical model and the simulation model of the system will be built. The implementation of the 3L-SNPC inverter and the MPC method for the D-STATCOM are presented in Chapter 3. Simulation and experimental results are given in Chapter 4. Finally, the thesis is concluded and the future works are provided in Chapter 5.

Chapter 2 Literature Review

2.1 Microgrids and DG System

According to the U.S. Department of Energy Microgrid Exchange Group, the microgrid is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid [7]. Comparing to the traditional electricity grid, it is a modern, localized, small-scale grid. The microgrid operates in two operating modes, one is connected to the conventional grid to allow power exchange, which is called grid connected and the other is independent of the conventional grid, called individual/islanded mode. That makes the microgrid more flexible [1].

The distributed energy resources in microgrids are also known as distributed generation. This electric power generation is on the customer side of the network, within distribution networks. DG systems usually use renewable energy sources, such as solar power, wind power and biomass. It plays an important role for the electric power distribution system in microgrids [8]. Grid-connected devices of electricity storage are also used in microgrids, and are often called a distributed energy storage system (DESS). By means of an interface, the DESS can help to manage the DG system in microgrids [9].

Other than DG systems and DESS, microgrids also contain power electronics interfaces and different kinds of loads. Together they enable the microgrids to collect energy from renewable and non-renewable sources and supply the power to the loads and consumers. The development and application of microgrids technology can lower the environmental

impacts and improve the security of power supply in microgrids. Fig 2.1 shows the structure of a microgrid.

Fig 2.1 Structure of a microgrid

However, there are numerous power quality problems in the microgrids, such as reactive power compensation, voltage and current harmonics, voltage sags and swells, voltage and current unbalance, and circulation of neutral current, impulse transients, and interruptions [1]. The flow of reactive power is caused mainly by the inductive and capacitive loads in microgrids, such as pumps and motors. The harmonics are generated by the electronics interfaces and nonlinear loads. These problems need to be solved to guarantee the power quality and the reliability of power supply of microgrids.

Among these problems, reactive power compensation and current harmonics in DG systems are the main concerns of this thesis.

2.2 Compensation Devices and D-STATCOM

Compensation devices are installed in DG systems to make compensation of reactive power and harmonics. There are mainly two categories of reactive power compensation devices. According to whether it is using semiconductor switching devices, reactive

power compensation devices can be divided into traditional reactive power compensation devices without switching devices and modern reactive power compensation devices using switching devices [10]. Fig 2.2.1 shows the classification of reactive power compensation devices.

Fig 2.2.1 Classification of reactive power compensation devices

The traditional reactive power compensation devices have simple structures and they are convenient for installation, operation and maintenance. However, they can only compensate for fixed reactive power and cannot be continuously adjusted. It also has the problem of rising harmonics in the system. Therefore, they cannot meet the requirements for reactive power compensation of the DG system in microgrids.

There are mainly two categories of modern reactive power compensation devices. One is called static var compensator (SVC). SVC is controlled by thyristors. The conduction angle is used to control the shunt reactor or switch in the capacitor to compensate for the reactive current. It can track the changes of reactive power and compensate reactive power by stages with low losses and ease of control. However, it is still difficult to achieve continuous compensation of reactive power, and the response speed is slow

when reactive power changes quickly [11].

The other is the static synchronous compensator (STATCOM). It is also known as the static var generator (SVG). STATCOM which is used on the load or distribution side is called distribution static synchronous compensator (D-STATCOM). It is a controllable full bridge circuit which is directly connected in parallel to the system or via reactors [11]. Fig 2.2.2 shows the schematic diagram of a D-STATCOM.

Fig 2.2.2 Schematic diagram of D-STATCOM

By controlling the current on the AC side, D-STATCOM can achieve the purpose of dynamic reactive power compensation. The advantages of D-STATCOM are that it can track reactive power changes continuously; the response of D-STATCOM is fast; and it can also compensate for harmonics [12].

The control of D-STATCOM is more complex than the other devices, but with the development of control technologies and the improvement of the manufacturing technologies, this is no longer a big problem. Therefore, D-STATCOM is more and more generally used to compensate the reactive power and harmonics of the DG system in microgrids [12].

2.3 Structure and Implementation of Three-Level Neutral Point Clamped Inverters

Since it was proposed in 1981, the three-level neutral point clamped (3L-NPC) inverter is receiving more and more attention [13]. Now it is an industrial standard inverter and is widely used. There are more and more researches on its applications in medium voltage scenarios, because the available semiconductors at that time did not have sufficient voltage blocking capability [14] [15]. Compared with the Two-Level (2L) inverter, the 3L-NPC inverter has the advantages of smaller output voltage and output current harmonics, half of the voltage and switching loss, which can effectively reduce the volume and weight of the passive components such as filters [16] [17]. Therefore, the 3L-NPC inverter has gradually shifted from the high-power medium-voltage application to the low-voltage grid-connected inverter system for photovoltaic, wind power and energy storage systems.

Compared with the 2L inverter, the main weakness of the 3L-NPC inverter is that usually it requires more diodes.

A conventional 3L-NPC inverter has 14 diodes and 12 transistors, while a T-Type 3L-NPC inverter has 12 diodes and 12 transistors [18]. A three-level simplified neutral point clamped (3L-SNPC) inverter can reduce the transistors to only 10 with anti-parallel connected diodes [17]. In a single-phase system, this 3L-SNPC inverter only requires 8 transistors. Fig 2.3.1 shows the structure of a T-Type 3L-NPC inverter and Fig 2.3.2 shows the structure of a 3L-SNPC inverter.

Fig 2.3.1 Structure of the T-Type 3L-NPC inverter

Fig2.3.2 Structure of the 3L-SNPC inverter

Another disadvantage of the NPC inverter is that it is prone to voltage drift and low-frequency voltage ripple at the neutral-point [19]. At present, there have been many studies on the control methods of the 3L-SNPC inverter, such as hysteresis control [17], vector control [20] and direct torque control [21]. However, some of these schemes are direct control methods. They do not use a modulator to synthesize a continuous output voltage, and some are designed for three-phase systems and are therefore more complicated. An MPC method can better fit different system models. Taking the problem of voltage balance of the neutral-point into consideration, it can realize the control of the 3L-SNPC inverter better. And the control logic is relatively simple.

The losses in the NPC system include power device loss, line loss, filter inductance, capacitance loss, etc., and each loss affects and correlates with each other. The loss of the power device is an important part of the system loss. The structure of the main circuit and the control strategy are of great significance to reduce the system loss and improve the efficiency of the inverter.

In this thesis, the model of the 3L-SNPC inverter is established. Furthermore, the MPC method for the 3L-SNPC inverter considering voltage balance is implemented. Simulation and experimental results will be shown to verify the performance of the proposed design.

2.4 Methods of Generating Reference Current Signals for D-STATCOM

Voltage Source Inverter (VSI) is an important component of the DSTATCOM. There are two main steps to control the VSI. The voltage on the source side V_s , the current on the load side I_L and the current on the source side I_s are given by sensors. The first step is using I_L and V_s to calculate the reference current I_{ref} for the source side. The second step is using a controller to let the I_s follows the calculated I_{ref} . After that, the control signals are generated to realize the control of VSI. Fig 2.4.1 shows the flow chart of controlling the D-STATCOM [22].

Fig 2.4.1 Flow chart of controlling D-STATCOM

The synchronous reference frame (SRF) theory and the instantaneous reactive power (IRP) theory are two kinds of algorithms which are most widely used to calculate the reference current.

The principle of SRF theory is to transform the sensed three-phase current I_{La} , I_{Lb} , I_{Lc} on the load side into a synchronously rotating d–q frame. The phase-locked loop (PLL) is used to process the three-phase voltage signals V_{sa} , V_{sb} , V_{sc} on the source side to generate unit voltage templates (sine and cosine signals) [23]. Using Clark's transformation, the three-phase current is transformed into two-phase signals as I_α and I_β , this transformation is defined as:

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \quad (2.1)$$

Then the Park's transformation is used to transform I_α and I_β into I_d and I_q . Using θ as the transformation angle, this transformation is defined as:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (2.2)$$

After that, a low pass filter (LPF) is used to filter these signals. The I_q signal is kept zero. Then using the reverse Park's transformation and Clark's transformation, the reference current on the source side is calculated [24]. Fig 2.4.2 shows the flow chart of calculating the reference current using SRF theory.

Fig 2.4.2 Flow chart of calculating reference current using SRF theory

The IRP theory is based on the Clark's transformation, transforming both the three-phase voltage signal on the source side and current signal on the load side into the two-phase, α - β frame. Then the active power signal and reactive power signal were computed in this frame. By keeping reactive power zero, the expected I_α and I_β can be calculated. Using reverse Clark's transformation, the reference current signals can also be generated.

This project is based on a balanced system, and because the IRP theory is more suitable for this kind of system, the IRP theory is used in this project instead of the SRF theory [1]. And to implement either SRF theory or IRP theory in a single-phase system, we have

$$\begin{aligned} I_{La} &= I_L; \\ I_{Lb} &= 0; \\ I_{Lc} &= 0. \end{aligned} \tag{2.3}$$

A detailed introduction and implementation of the IRP theory will be discussed in Chapter 3.

2.5 Model Predictive Control Methods and Applications

Except from methods used to extract the reference current, the control method also has influence on the performance of the D-STATCOM. The essence of D-STATCOM current control is to make the output current (I_{sh}) of D-STATCOM track the expected current signal quickly and with small error under the premise of satisfying the switching frequency of the switching device. In this project, the MPC method is used to control the current on the source side. The traditional hysteresis band control method is also briefly introduced for comparison.

Hysteresis current control (HCC) is based on the pulse width modulated (PWM) technology. The HCC method is a real-time control method and if the width of the hysteresis band is fixed, the current tracking error range is also fixed [25]. Fig 2.5.1

shows the schematic of the hysteresis current control.

However, the switching frequency of switching devices are not stable. This can bring more harmonics to the system sometimes. And another problem is that the speed of response is not fast enough when the current changes quickly [26]. In addition, hysteresis control is also difficult to deal with the problem of voltage imbalance at the clamp point [23]. Hysteresis control has been abandoned because of its shortcomings. It is substituted by vector control presently.

Fig 2.5.1 Schematic of hysteresis current control

Developing the predictive model of the integrated system is the most important step of MPC. The present output current of the D-STATCOM $I_{sh}(k)$ is given to the predictive model of the system to calculate the possible current $I_{sh}(k + 1)$ of the next time step.

Because there are many different combinations of the switching status of the switching devices, the $I_{sh}(k + 1)$ also has a number of different values corresponding to different switching status. Comparing these different $I_{sh}(k + 1)$ value with the expected current of D-STATCOM of the next time step $I_{sh_ref}(k + 1)$ and select an option that can get the minimum error, the switching status can also be determined. This is called the cost function minimization block. According to the switching status determined by this block, the switching signal of the next step can be determined and generated to control the VSI [27]. Fig 2.5.2 shows the schematic of MPC.

Fig 2.5.2 Schematic of MPC

One of the most important advantages of MPC is that signal modulation is not needed and direct digital control can be implemented because PWM is not used. And the switching frequency is also controllable using MPC. Considering the time step T_s , the maximum of the frequency is $\frac{1}{T_s}$. Therefore, using MPC can make the performance of D-STATCOM better and the harmonics in the system can also be better controlled [28].

The MPC method can also solve the voltage balance problem of the DC side capacitor. From the energy point of view, when the voltage difference between the upper capacitor C_1 and lower capacitor C_2 exceeds a certain limit, priority is given to voltage balance to determine the switching state of the diodes. For example, when the voltage of C_1 is higher than the DC source voltage of C_2 by more than 10%, and there is still current flowing into C_1 to charge it, the voltage of C_1 will continue to increase. Under this condition, the switching strategy must be changed to charge C_2 in the next time step, instead of considering the switching strategy for optimal reactive power compensation given by MPC. The specific switching logic will be introduced in Chapter 3.

Chapter 3 Theoretical Basis and Models of the System

3.1 System Configuration

Fig 3.1.1 is the circuit diagram of the D-STATCOM system. The system includes the main structure of the D-STATCOM. The DC side is a dual-buck converter that can output three-level voltages. Connected to it is a traditional inverter. Together they form the 3L-SNPC inverter. The power supply side simulates a single-phase AC power grid. The non-linear load is composed of a resistor, a diode-controlled inductor and a capacitor, which simulates the non-linear load in the DG system. R represents the impedance of the transmission line measured by the power grid. Its influence is not the main consideration of this subject and its value is 0.1Ω . The power grid is a three-phase voltage source with line voltage of 400V and frequency of 50Hz. Only phase a is used in this project. Other important parameters are shown in Table I. Table II shows the important variables of the system and their corresponding meanings.

We assume that only one phase for control is used. We acknowledge a three-phase system is not a simple combination of three single-phase systems. In addition to the assumption of a perfectly balanced system, this also implies that there is no offset in the measured signal.

Fig 3.1.1 Circuit diagram of the D-STATCOM system

Table I. parameter values of the system

Description	D-STATCOM parameters		Description	System parameters	
	Symbol	Value		Symbol	Value
DC source voltage	V_{dc}	50V	MPC time step	T_s	40 μ S
DC side capacitors	C_1, C_2	2.2mF	Grid-connected inductor	L_{sh}	13mH

Table II. variables of the system and corresponding meanings

Description	Symbol	Description	Symbol
Voltage of the source	V_s	Voltage of the upper capacitor	V_p
Current of the source	I_s	Current injected into the upper capacitor	I_1
Voltage of the load	V_L	Voltage of the lower capacitor	V_n
Current of the load	I_L	Current injected into the lower capacitor	I_2
Voltage of the grid-connected inductor	v_x	Output voltage of the Three-Level DC source	V_d
Current of the grid-connected inductor	I_{sh}	Output voltage of the D-STATCOM	V_f

Most of the variables will be measured by sensors in the system. The 8 IGBTs contained in the D-STATCOM are marked as S_1 - S_8 , and they are marked in Fig 3.1.1 accordingly. Control signals will be given to them by an MPC controller. Fig 3.1.2 shows the Simulink model of the integrated system.

Fig 3.1.2 Simulink model of the integrated system

The reactive power in the system is mainly generated by capacitive loads and inductive loads. In most cases, due to the presence of inductive loads such as motors, compressors and pumps, the system appears a lagging power factor. In this thesis, the linear load is set as an inductive load R_{L1} to simulate the linear load in real systems. Fig 3.1.3 shows the Simulink model of the load.

Fig 3.1.3 Simulink model of the load

The harmonics in the real system are generated by both the nonlinear loads and the power electronics interfaces. In this thesis, a bridge circuit composed of four diodes, $D_1 - D_4$, simulates this situation. The value of the variables on the load side are shown in Table III.

Table III. parameter values of the system

Description	D-STATCOM parameters		Description	System parameters	
	Symbol	Value		Symbol	Value
Linear load	R_{L1}	6.5mH	Non-Linear load	C_{L1}	3.9mF
Non-Linear load	R_{L2}	6.5mF, 20Ω	Non-Linear load	R_{L3}	20Ω

3.2 Logic of the 3L-SNPC Inverter Considering Voltage balance

Under ideal condition, the capacitances of C_1 and C_2 are equal, so their voltages V_p and V_n are also equal. Both of them are half of the voltage of the DC source. We then have (3.1). It is the basis of the DC source to output the three-level voltage.

$$V_p = V_n = \frac{1}{2}V_{dc} \quad (3.1)$$

By controlling the state of switches S_5 - S_8 , three output voltage levels can be generated. Combined with the traditional inverter, S_1 - S_4 , five different voltages can be generated: $0, +V_{dc}, -V_{dc}, +\frac{1}{2}V_{dc}$ and $-\frac{1}{2}V_{dc}$.

As mentioned in Chapter 2, the voltage balance of the neutral point must be prioritized. For the voltage difference between C_1 and C_2 , a bound is set as 20% of the DC source (10V). Denoted the voltage difference as D, D is given by:

$$D = V_p - V_n \quad (3.2)$$

When D is higher than 10 or lower than -10, the voltage balance strategy is executed first, regardless of the optimal voltage selection given by MPC. Whether to use the upper capacitor C_1 or the lower capacitor C_2 , the current injected into the capacitor needs to be considered. For example, when the voltage of the upper capacitor C_1 is higher than the lower capacitor C_2 and exceeds the bound D, and the current is still injected into the upper capacitor at this time, only the lower capacitor can be used in the next time step

so that the current will be injected into the lower capacitor. In this way the voltage difference between the two capacitors can be reduced as much as possible. Conversely, if the voltage of the upper capacitor is lower than the lower capacitor and exceeds the bound D , and the current still flows out of the lower capacitor C_2 at this time, we can only use the lower capacitor in the next time step.

Since the voltage balance strategy is executed first, the bound cannot be set too small, which will reduce the compensation of the D-STATCOM.

Taking into account the above factors, the switch state selection strategy considering voltage balance is settled. The specific logic is shown in Table IV. According to the above logic, the MATLAB/Simulink code used to generate the control signal is shown in Appendix A.1.

Table IV. switching logic considering voltage balance

Output voltage of the D-STATCOM	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	Remarks
$\frac{1}{2}V_{dc}$	1	0	0	1	1	0	0	1	$D \geq 10, I_1 \geq 0$
$-\frac{1}{2}V_{dc}$	0	1	1	0	1	0	0	1	$D \geq 10, I_1 \geq 0$
$\frac{1}{2}V_{dc}$	1	0	0	1	0	1	1	0	$D \leq -10, I_1 < 0$
$-\frac{1}{2}V_{dc}$	0	1	1	0	0	1	1	0	$D \leq -10, I_1 < 0$
V_{dc}	1	0	0	1	0	0	1	1	$10 \geq D \geq -10$
$-V_{dc}$	0	1	1	0	0	0	1	1	$10 \geq D \geq -10$
$\frac{1}{2}V_{dc}$	1	0	0	1	1	0	0	1	$D \geq 0, I_1 \geq 0$
$-\frac{1}{2}V_{dc}$	0	1	1	0	1	0	0	1	$D \geq 0, I_1 \geq 0$
$\frac{1}{2}V_{dc}$	1	0	0	1	0	1	1	0	$D < 0, I_1 < 0$
$-\frac{1}{2}V_{dc}$	0	1	1	0	0	1	1	0	$D < 0, I_1 < 0$
0	1	0	1	0	1	0	0	1	$10 \geq D \geq -10$

3.3 Reference Current Calculation Using Instantaneous Reactive Power Theory

Two widely used theories for calculating the reference current were introduced in Section 2.4 and the IRP theory is selected for this project. In this section, the algorithm for calculating the reference current using this theory will be described in detail. And the Simulink model will also be established.

There are mainly five steps of calculating the reference current using the IRP theory.

The first is the Clark's transformation. The second is instantaneous power calculation. The third is compensating power selection. The fourth is alpha-beta current calculation and the last is the reverse Clark's transformation. Fig 3.3.1 shows the flow chart of calculating the reference current using IRP theory.

Fig 3.3.1 Flow chart of calculating reference current using IRP theory

3.3.1 Clark's transformation

The a, b and c axes span apart from each other by $2\pi/3$ in the a-b-c coordinates, and they are fixed on the same plane. While the α and β axes are orthogonal coordinates. The instantaneous space phasors $\dot{V}_a$ and $\dot{I}_{La}$ are set on the a axis. It is the same for $\dot{V}_b$, $\dot{I}_{Lb}$, $\dot{V}_c$ and $\dot{I}_{Lc}$. Using the Clark's transformation, these phasors can be transformed into α - β coordinates as follows [29]:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3.3)$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \quad (3.4)$$

Under ideal condition, V_L is equal to V_s . The Simulink model of transforming V_s from the a-b-c coordinates into the α - β coordinates is shown in Fig 3.3.2 and the Simulink

model of transforming IL from the a-b-c coordinates into the α - β coordinates is shown in Fig 3.3.3.

Fig 3.3.2 Simulink model used to transform V_s into α - β coordinates

Fig 3.3.3 Simulink model of transforming I_L into α - β coordinates

3.3.2 Instantaneous power calculation

Using p to represent the active power and q to represent the reactive power, they can be computed using the α - β coordinates-based equation:

$$p = V_{\alpha}I_{\alpha} + V_{\beta}I_{\beta} \quad (3.5)$$

$$q = -V_{\beta}I_{\alpha} + V_{\alpha}I_{\beta} \quad (3.6)$$

The p and q can also be defined in matrix form as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_{\alpha} & V_{\beta} \\ -V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} I_{\alpha} \\ I_{\beta} \end{bmatrix} \quad (3.7)$$

The Simulink model of calculating the instantaneous active power p and reactive power

q is shown in Fig 3.3.4.

Fig 3.3.4 Simulink model of calculating p and q

3.3.3 Compensating power selection

For the instantaneous active power p , it has two components, the average (DC) component $\bar{p}$ and the oscillatory (AC) component $\tilde{p}$. The reactive power q also has two components, the average (DC) component $\bar{q}$ and the oscillatory component $\tilde{q}$. The p and q can be defined as:

$$p = \bar{p} + \tilde{p} \quad (3.8)$$

$$q = \bar{q} + \tilde{q} \quad (3.9)$$

Since the source gives only the DC component of the active power, only the average component $\bar{p}$ is needed in p and the reactive power q is kept 0 for the calculation of the reference current I_{ref} .

The Simulink model of selecting the compensating power $\bar{p}$ is shown in Fig 3.4.5. A low-pass filter is used to remove the AC component in q .

Fig 3.3.5 Simulink model of selecting the compensating power $\bar{q}$

3.3.4 Alpha-beta current calculation

The reference current on the source side I_{ref} based on the α - β coordinates are I_{α}^* and I_{β}^* .

They are expressed as:

$$\begin{bmatrix} I_{\alpha}^* \\ I_{\beta}^* \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} V_{\alpha} & -V_{\beta} \\ V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \quad (3.10)$$

Δ is defined as:

$$\Delta = V_{\alpha}^2 + V_{\beta}^2 \quad (3.11)$$

Fig 3.3.6 shows the Simulink model of calculating the reference α - β current.

Fig 3.3.6 Simulink model of calculating the reference α - β current

3.3.5 Reverse Clark's transformation

The reverse Clark's transformation is used to calculate the reference current I_{ref} on the load side. It is defined as:

$$\begin{bmatrix} I_{refa} \\ I_{refb} \\ I_{refc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_0^* \\ I_\alpha^* \\ I_\beta^* \end{bmatrix} \quad (3.12)$$

In this equation, I_0^* is the zero-sequence component. In this project the value of I_0^* is 0.

Fig 3.3.7 shows the Simulink model used to calculate the reference a-b-c current on the source side.

Fig 3.3.7 Simulink model of calculating the reference a-b-c current

3.4 Principle and Application of Model Predictive Control Considering Voltage Balance

3.4.1 Mathematical model and dynamic model of the system

In order to discuss the dynamic model and the predictive model of the system, the steady-state mathematical model of the system needs to be established. A single-phase D-STATCOM system with a DC voltage source is introduced in this section. Fig 3.4.1 shows the topology of this single-phase D-STATCOM system.

Fig 3.4.1 Topology of the single-phase D-STATCOM system

Under the ideal condition without D-STATCOM, the angle δ between $\dot{V}_s$ and $\dot{I}_s$ should be 0° and the power factor $\cos\delta$ should be 1. Fig 3.4.2 shows the ideal phasor diagram of the system.

Fig 3.4.2 Ideal phasor diagram of the system

However, due to the inductive devices such as motors and pumps on the load side, $\dot{I}_s$ actually lags behind $\dot{V}_s$ by angle δ . Fig 3.4.3 shows the phasor diagram using $\dot{V}_s$ as the reference phasor without D-STATCOM.

Fig 3.4.3 Phasor diagram without D-STATCOM

Fig 3.4.4 shows the phasor diagram of the system with the D-STATCOM. It can also explain why the D-STATCOM can compensate the reactive current on the source side.

Fig 3.4.4 Phasor diagram with D-STATCOM

The steady-state model of the D-STATCOM system can be described as:

$$\text{KVL: } \dot{V}_s = \dot{V}_L = \dot{V}_f - \dot{V}_x \quad (3.13)$$

$$\text{KCL: } \dot{I}_L - \dot{I}_s - \dot{I}_{sh} = 0 \quad (3.14)$$

Using formulas (3.13) and (3.14), the dynamic model of the D-STATCOM system can also be established. In the dynamic model of the D-STATCOM system, the relationship between V_x and I_{sh} can be described by the following equation:

$$V_x = L_{sh} \frac{dI_{sh}}{dt} \quad (3.15)$$

Substituting equation (3.15) into equation (3.13), the dynamic model of the system can be derived as (3.16):

$$V_f - L_{sh} \frac{dI_{sh}}{dt} - V_s = 0 \quad (3.16)$$

It can also be described as:

$$\frac{dI_{sh}}{dt} = \frac{1}{L_{sh}} V_f - \frac{1}{L_{sh}} V_s \quad (3.17)$$

3.4.2 Predictive model of the system

The $\frac{dI_{sh}}{dt}$ can be regarded as the rate of change of I_{sh} in one time step T_s . Denote the value of I_{sh} at present as $I_{sh}(k)$ and the value of I_{sh} at the next time step as $I_{sh}(k+1)$. $\frac{dI_{sh}}{dt}$ can be described as:

$$\frac{dI_{sh}}{dt} = \frac{1}{T_s} [I_{sh}(k+1) - I_{sh}(k)] \quad (3.18)$$

Then denote the value of V_f at present as $V_f(k)$ and the value of V_s at present as $V_s(k)$, the predictive model of the D-STATCOM system can be described as:

$$I_{sh}(k+1) - I_{sh}(k) = \frac{T_s}{L_{sh}} [V_f(k) - V_s(k)] \quad (3.19)$$

The expected current of the D-STATCOM of the next time step $i_{shref}(k+1)$ can then be calculated by:

$$I_{shref}(k+1) = I_{sh}(k+1) = I_{sh}(k) + \frac{T_s}{L_{sh}} V_f(k) - \frac{T_s}{L_{sh}} V_s(k) \quad (3.20)$$

3.4.3 Cost function minimization

The cost function minimization means to get the minimized value of the error function. The error function represents the absolute value of the error between the expected current of the D-STATCOM of the next time step $i_{shref}(k+1)$ and the real current of the D-STATCOM of the next time step $I_r(k+1)$. It can be defined as:

$$e = |I_{shref}(k+1) - I_r(k+1)| \quad (3.21)$$

The IGBTs in the D-STATCOM system have different combinations of switching status, V_d has 5 different values. According to the equation (3.21), e also has 5 possible values, $e_1 - e_5$. Find the minimum of the possible error e_{min} using

$$e_{min} = \min\{e_1, e_2, e_3, e_4, e_5\} \quad (3.22)$$

Then the corresponding value of V_d can be found, the status of the switches in the next time step can be decided accordingly. The specific switching logic is given in Table III in Section 3.2. And the corresponding switching signal can also be generated after that [30].

Voltage balance is still a priority. As discussed in Section 3.2, if the voltage difference between the two capacitors on the DC side exceeds the bound, the switching strategy of voltage balance should be implemented first without considering the optimal choice given by the MPC.

Furthermore, when the voltage difference between the two capacitors on the DC side does not exceed the limit, a certain switching strategy can also be used to balance the voltage on the two capacitors as much as possible. The specific switching strategy has also been given in Table III.

3.4.4 Simulink model of the MPC based method

Fig 3.4.5 shows the Simulink model of the MPC based method. A programmable block is used to implement the algorithm stated in the previous sections. The output of this MPC controller U is used to represent the selection of the output voltage of the D-STATCOM.

Fig 3.4.5 Simulink model of the MPC base method

And U is given to the switching strategy selection block shown in Fig 3.4.6. Considering both the voltage balance and the MPC method, the switching signals for the D-STATCOM can be generated. According to the above algorithm, the MATLAB/Simulink code for the most suitable output voltage of D-STATCOM is shown in Appendix A.2.

Fig 3.4.6 Simulink model of the switching strategy selection

Chapter 4 Simulation Results and Analysis

4.1 Experimental Platform and Environment

The simulation in Chapter 4 is based on the Simulink platform of MATLAB and it is discrete time simulation. Even if the algorithm used by the control method is very complex, discrete-time simulation can still get good results after a long time of calculation. However, this is unacceptable in real systems. If the model or algorithm used is too complex, then the controller may not complete the calculation within one time step or the accuracy of calculation is not enough. This will make the control scheme unable to achieve the expected effect. On the other hand, due to the limitation of the switching frequency of the IGBTs, the time step T_s cannot be set too small.

The objective of using OPAL-RT to do the real time simulation and using dSPACE to do the control-hardware-in-the-loop (CHIL) experiment are to verify that the MPC based algorithm is not too complex for the computer and the controller can run independently, so it can be used in real systems. The experimental equipment is shown in Fig 4.1. In the CHIL experiment, the internal signals of the system are collected and transmitted to dSPACE, and the MPC and switch selection logic are stored and executed by dSPACE. The obtained control signal is transmitted back to the real-time simulation model loaded in OPAL-RT.

Fig 4.1 Real-time simulation and CHIL experimental equipment

4.2 Simulation Results

4.2.1 Off-line simulation in MATLAB

Without the D-STATCOM, the waveform of the voltage on the source side V_s is shown in Fig 4.2.1 and the waveform of the current on the source side I_s is shown in Fig 4.2.2.

Fig 4.2.1 Voltage waveform on the source side (without D-STATCOM)

Fig 4.2.2 Current waveform on the source side (without D-STATCOM)

The waveform of the voltage on the load side V_L is the same as V_s . Without the D-STATCOM, the waveform of the current on the load side I_L is the same as I_s .

Fast Fourier transform (FFT) is used to analyze the harmonics in I_s . Fig 4.2.3 shows the harmonics components of I_s . The total harmonic distortion (THD) of I_s without DSTATCOM is 20.52%.

Fig 4.2.3 Harmonics components of I_s (without D-STATCOM)

With the MPC based D-STATCOM using the 3L-SNPC inverter, the waveforms of the voltage and the current on the load side are shown in Fig 4.2.4 and Fig 4.2.5.

Fig 4.2.4 Voltage waveform on the source side (with D-STATCOM)

Fig 4.2.5 Current waveform on the source side (with D-STATCOM)

It can be seen from Fig 4.2.5 that the current waveform on the source side is close to sinusoidal and remains in phase with the power supply voltage. Fig 4.2.6 shows the harmonics components of I_s . The THD of I_s with D-STATCOM is reduced to 2.62%.

Fig 4.2.6 Harmonics components of I_s (with D-STATCOM)

Check the status of the 3L-SNPC inverter. The waveforms of its output voltage V_f and current I_{sh} are shown in Fig 4.2.7 and Fig 4.2.8.

Fig 4.2.7 Output voltage waveform of the 3L-SNPC

Fig 4.2.8 Output current waveform of the D-STATCOM

It can be seen that the output voltage of the 3L-SNPC inverter has 3 levels, 0 , $\pm V_{dc}$ and $\pm \frac{1}{2} V_{dc}$. This has satisfied the basic goal of this project. The voltage waveform of the DC side capacitor C_1 and C_2 is shown in Fig 4.2.9. It can be seen that the voltage difference is maintained within the set bound, and the ripple is small.

Fig 4.2.9 Voltage waveforms of DC side capacitors

After the verification of MATLAB/Simulink offline simulation, the MPC based D-STATCOM using 3L-SNPC inverter has achieved the purpose of this project, and further verification will be carried out in real-time simulation.

4.2.2 Real-time simulation using OPAL-RT

The real-time simulation means that the time the program runs is consistent with the real time. For example, a simulation program is built for the response of the inertial link to a unit step signal. The simulation time is 10 seconds, and the program is likely to run in a few milliseconds and gives calculation results. This means that the process is non-real time. The time it takes depends on the complexity of the model, computer performance and other factors, so this time is uncontrollable. However, when performing simulations, especially when it comes to hardware-in-loop (HIL) simulation, it is often required that the response of the program to be consistent with the real time [31]. Therefore, it is necessary to verify this project in a real-time simulation system.

In order to verify the performance of the MPC based D-STATCOM with a 3L-SNPC inverter, the first concern is the source side voltage and current as they directly reflect the effect of reactive power compensation. Fig 4.2.10 and Fig 4.2.11 shows the waveform of the voltage and the current on the source side. The current waveform on the load side is shown in Fig 4.2.12 for comparison.

Fig 4.2.10 Voltage waveform on the source side (real-time simulation using OPAL-RT)

Fig 4.2.11 Current waveform on the source side (real-time simulation using OPAL-RT)

Fig 4.2.12 Current waveform on the load side (real-time simulation using OPAL-RT)

Compared with the off-line simulation results in MATLAB, the current on the source side is still close to sinusoidal and remains in phase with the voltage on the source side. In real-time simulation, the D-STATCOM proposed in this project can still achieve a good reactive power compensation effect.

Check the status of the 3L-SNPC inverter. The waveforms of its output voltage V_f and current I_{sh} are shown in Fig 4.2.13 and Fig 4.2.14. The voltage waveform of the DC side capacitor C_1 and C_2 is shown in Fig 4.2.15.

The experiment in MATLAB/Simulink is actually an offline simulation experiment. The main difference between the real-time simulation and offline simulation is that the response speed of the simulation model is different from that of the real system.

The response speed of the model in offline simulation is slower than the response speed of the real system. For example, to observe the operating state of the model running for about 1s, the time required for simulation calculation is usually more than 1s. The result obtained is more "accurate", or more in line with the ideal result.

The model response speed of the real-time simulation is the same as that of the real system. The actual time corresponding to 1s of the model simulation run is 1s. Due to the large amount of calculation of the power electronic system model and the limitation of the real system computing ability, the results obtained will not be that "accurate". In other words, they will not be so in line with the ideal results.

Fig 4.2.13 Output voltage waveform of the 3L-SNPC (real-time simulation using OPAL-RT)

Fig 4.2.14 Output current waveform of the D-STATCOM (real-time simulation using OPAL-RT)

Fig 4.2.15 Voltage waveforms of DC side capacitors (real-time simulation using OPAL-RT)

4.2.3 Control-hardware-in-the-loop experiment

After the real-time simulation verification in OPAL-RT, the control module can be loaded in dSPACE to perform CHIL experiments for verification of the D-STATCOM proposed in this project. Results and waveforms are shown in Fig 4.2.16 – Fig 4.2.20.

Fig 4.2.16 Voltage waveform on the source side (CHIL)

Fig 4.2.17 Current waveform on the source side (CHIL)

Compared with the results of real-time simulation on the OPAL-RT, the voltage and current waveforms on the source side obtained from the CHIL experiment are a little worse. The performance of reactive power compensation of the D-STATCOM is further reduced. In particular, the current harmonics on the source side is increased.

Fig 4.2.18 Output voltage waveform of the 3L-SNPC (CHIL)

Fig 4.2.19 Output current waveform of the D-STATCOM (CHIL)

Observing the output voltage and current of the D-STATCOM, the performance of the D-STATCOM is relatively satisfactory. The output voltage can still maintain three levels, and the current waveform is still close to the calculated reference current.

Fig 4.2.20 Voltage waveforms of DC side capacitors (CHIL)

The voltage waveform of the DC side capacitor is also slightly worse than the result obtained from real-time simulation, but the voltage difference between the two capacitors is still maintained within the settled bound.

Chapter 5 Conclusions and Future Works

5.1 Conclusions

The mathematical model of the integrate system was formulated and built on the Simulink platform. Then two theories used for calculating the reference current, the SRF theory and the IRP theory, were discussed in this project. The IRP theory was selected and implemented in this project. Then the simplified circuit model of the 3L-NPC inverter is proposed and implemented in this thesis. The problem of voltage balance is also considered. After that, the MPC based method is implemented. After completing the theoretical analysis, the integrated system is built in the Simulink platform. And finally, the off-line simulation on MATLAB/Simulink platform, the real-time simulation on the OPAL-RT and CHIL experiment are carried out to verify the feasibility and effect of the MPC based D-STATCOM with the 3L-SNPC inverter proposed in this project. The conclusions are as follows:

- 1) VSI has several advantages and is mostly used in the D-STATCOM system.
- 2) The IRP theory is more suitable for three-phase symmetric systems so it is used in this project to calculate the reference current.
- 3) The MPC based D-STATCOM can effectively compensate the reactive current on the source side and reduce harmonics.
- 4) The 3L-SNPC inverter in this project can output three-level voltage, and the voltage balance strategy can keep the voltage difference between the two capacitors on the

DC side within a certain bound.

- 5) The performance of the MPC base D-STATCOM can be better by reducing the time step T_s . But this must consider the limitation of the switching frequency of IGBTs and the computer performance.
- 6) The real-time simulation using the OPAL-RT and CHIL experiment proved that the MPC based controller can run independently and can be used in real systems.

5.2 Future Works

After the modeling and simulation of the MPC base D-STATCOM with the 3L-SNPC inverter, there still remains some problems and some works can be done in the future.

- 1) In this project, the reactive power and harmonics of the load change steadily and periodically, and the impact on the DC side capacitor voltage is relatively limited. Under more serious conditions such as the voltage difference between the two capacitors on the DC side exceeding the bound, the performance of D-STATCOM and the effect of the neutral point voltage balance strategy are still to be tested.
- 2) The hardware of D-STATCOM can be built for further simulation works and experiments.
- 3) The power quality in DG system largely depends on the type of grid-connected inverter interface and its control performance [32]. Low-power DG usually uses inverter with output inductor L filter as grid-connected interface [33]. High-power DG usually uses inverter with output LCL filtering as the grid-connected interface. The main reason is that the switching frequency of high-power inverters is generally low. It is necessary to filter out the harmonics near the switching frequency and its integer multiples. The inductive filtering method requires a larger inductance, high cost and large volume [34]. Using LCL filter method can select a smaller inductor to achieve the same filtering effect, and the dynamic performance is better. The application of LCL filter to this project is also of great research significance.

Bibliography

- [1] M. T. L. Gayatri, A. M. Parimi and A. V. P. Kumar (2018). A review of reactive power compensation techniques in microgrids. *Renewable and Sustainable Energy Reviews*, 81(August 2017), 1030–1036. <https://doi.org/10.1016/j.rser.2017.08.006>
- [2] V. M. Awasthi (2016). Reactive Power Compensation using. 583–585.
- [3] H. Vahedi and K. Al-haddad (2015). Single-DC-Source Five-Level CHB Inverter with Sensor-Less Voltage Balancing. 4494–4499.
- [4] K. Corzine, Y. Familant and S. Member (2002). A New Cascaded Multilevel H-Bridge Drive.
- [5] G. Sahu (2015). Model Predictive Control of DSTATCOM for Power Quality Improvement: Modeling , Simulation and Analysis-Part1.
- [6] E. Das and A. Banerji (2017). State of Art Control Techniques for DSTATCOM (December). <https://doi.org/10.1109/CALCON.2017.8280737>
- [7] <https://building-microgrid.lbl.gov/about-microgrids>
- [8] Ackermann, T. (2001). Distributed generation : a definition. 57, 195–204.
- [9] <https://en.wikipedia.org/wiki/Microgrid>
- [10] J. Dixon, L. Morán, J. Rodríguez and R. Domke (2005). Reactive Power Compensation Technologies: State-of-the-Art Review. 93(12).
- [11] D. Vaishnavi and T. S. Subashini, “Power Electronics and Renewable Energy Systems,” *Lect. Notes Electr. Eng.*, vol. 326, no. July, pp. 1225–1233, 2015.
- [12] O. P. Mahela and A. G. Shaik, “A review of distribution static compensator,” *Renew. Sustain. Energy Rev.*, vol. 50, pp. 531–546, 2015.
- [13] A. Nabae, I. Takahashi, and H. Akagi, “A new neutral-point-clamped pwm inverter,” *Industry Applications, IEEE Transactions on*, vol. IA-17, no. 5, pp. 518–523, 1981.
- [14] J. Rodriguez, S. Bernet, P. K. Steimer, and I. E. Lizama, “A survey on neutral-point-clamped inverters,” *Industrial Electronics, IEEE Transactions on*, vol. 57, no. 7, pp. 2219–

2230, 2010.

- [15] J. Rodriguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 2930–2945, 2007.
- [16] R. Teichmann and S. Bernet, "A comparison of three-level converters versus two-level converters for low-voltage drives, traction, and utility applications," *Industry Applications, IEEE Transactions on*, vol. 41, no. 3, pp. 855–865, 2005.
- [17] R. Rojas, T. Ohnishi, and T. Suzuki, "Simple structure and control method for a neutral-point-clamped pwm inverter," in *Power Conversion Conference, 1993. Yokohama 1993., Conference Record of the*, pp. 26–31.
- [18] Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications.
- [19] M. Schweizer, S. Member and J. W. Kolar (2013). Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications. 28(2), 899–907.
- [20] A. Lange and B. Piepenbreier. Space Vector Modulation for Three-Level Simplified Neutral Point Clamped (3L-SNPC) Inverter.
- [21] D. Mohan, X. Zhang, and G. Foo, "Direct torque control of sparse three level inverter fed low voltage ipmsm drive," in *2015 IEEE International Electric Machines & Drives Conference (IEMDC)*, pp. 929–935.
- [22] Q. Song and W. Liu, "Control of a cascade STATCOM with star configuration under unbalanced conditions," *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 45–58, 2009.
- [23] A. Rohani, "Modeling and Control of DSTATCOM using adaptive hysteresis band current controller in Three-Phase Four-Wire Distribution systems," *5th Power Electron. Drive Syst. Technol. Conf.*, no. Pedstc, pp. 291–297, 2014.
- [24] S. P. Gopal and D. R. Patil, "Hysteresis Band Current Controller for Voltage Regulation and Harmonic Mitigation using DSTATCOM," *2016 Int. Conf. Comput. Power, Energy, Inf. Commun. ICCPEIC 2016*, pp. 707–712, 2016.
- [25] D. Sreenivasarao, P. Agarwal, and B. Das, "Neutral current compensation in three-phase,

-
- four-wire systems: A review,” *Electr. Power Syst. Res.*, vol. 86, pp. 170–180, 2012.
- [26] R. Sreejith, N. M. Pindoriya, and B. Srinivasan, “A novel control algorithm based DSTATCOM for load compensation,” *J. Phys. Conf. Ser.*, vol. 659, no. 1, 2015.
- [27] M. Siami, D. A. Khaburi, and J. Rodriguez, “Simplified Finite Control Set-Model Predictive Control for Matrix Converter-Fed PMSM Drives,” *IEEE Trans. Power Electron.*, vol. 33, no. 3, pp. 2438–2446, 2018.
- [28] G.W.Moon, “Predictive current control of distribution static compensator for reactive power compensation,” *IEE Proc. - Gener. Transm. Distrib.*, vol. 146, pp. 515–520, 1999.
- [29] B. Singh and J. Solanki, “A Comparison of Control Algorithms for DSTATCOM,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 7, pp. 2738–2745, 2009.
- [30] A. Ahmadi, M. Ahmadifar, and S. Ahmadi, “Three-Phase Inverter Control by Model Predictive Control,” vol. 4, no. 1, pp. 81–86, 2015.
- [31] J. Bélanger, P. Venne and S. Member. The What, Where and Why of Real-Time Simulation. 37–49.
- [32] F. Blaabjerg, Z. Chen, S. B. Kjaer. Power electronics as efficient interface in dispersed power generation systems[J]. *IEEE Transactions on Power Electronics*, 2004, 19(5): 1184-1194.
- [33] Y. Xue, L. Chang, S. B. Kjaer. Topologies of single-phase inverters for small distributed power generators: an overview[J]. *IEEE Transactions on Power Electronics*, 2004, 19(5): 1305-1314.
- [34] C. Energy (2014). Design of the Controller of the Single Phase PV Grid-Connected Inverter with LCL Filter.

Appendix A

A.1 MATLAB/Simulink code used to generate the control signal

```
function [S1, S3, S5, S6] = signal_logic(U,Vp,Vn, I1, I2)
    delta=Vp-Vn;
    Bound=8;
    if (delta>=Bound) && (U>0)
        %half dc link, up arm, positive
        S1=1;

        S3=0;

        S5=1;
        S6=0;

    elseif (delta>=Bound) && (U<0)
        %half dc link, up arm, negative
        S1=0;

        S3=1;

        S5=1;
        S6=0;

    elseif (delta<=-Bound) && (U>0)
        %half dc link, low arm, positive
        S1=1;

        S3=0;

        S5=0;
        S6=1;

    elseif (delta<=-Bound) && (U<0)
        %half dc link, low arm, negative
        S1=0;

        S3=1;

        S5=0;
        S6=1;
```

```

elseif (delta>-Bound) && (delta<Bound) && (U==1)
    %full dc link,positive
    S1=1;

    S3=0;

    S5=0;
    S6=0;

elseif (delta>-Bound) && (delta<Bound) && (U==-1)
    %full dc link,negative
    S1=0;

    S3=1;

    S5=0;
    S6=0;

    elseif (delta>-Bound) && (delta<Bound) && (U==1/2) && (delta>=0)
        %half dc link,up arm, positive
        S1=1;

        S3=0;

        S5=1;
        S6=0;

    elseif (delta>-Bound) && (delta<Bound) && (U==1/2) && (delta<0)
        %half dc link,low arm, positive
        S1=1;

        S3=0;

        S5=0;
        S6=1;

    elseif (delta>-Bound) && (delta<Bound) && (U==-1/2) && (delta>=0)
        %half dc link,up arm, negative
        S1=0;

        S3=1;

        S5=1;
        S6=0;

    elseif (delta>-Bound) && (delta<Bound) && (U==-1/2) && (delta<0)
        %half dc link,low arm, negative
        S1=0;

        S3=1;

        S5=0;
        S6=1;

else
    %U=0,
    S1=1;

```

```

    S3=1;

    S5=1;
    S6=0;

end

end

```

A.2 MATLAB/Simulink code for the most suitable output voltage of D-STATCOM

```

function [ U1, U, x_opt] =
singlecontrol(Is_ref, If, IL, Is, Vs, x_opt_kml)

% Optimum vector and measured current at instant k-1

Vdc=50;

Lf=13e-3;
Ts=50e-6;
A=[1 Ts/Lf 0 0; 0 1 0 0; 1 Ts/Lf 0 1; 0 0 0 1];
B=[-Vdc*Ts/Lf; 0; -Vdc*Ts/Lf; 0];
C=[0 0 1 0];

NP=2;
NC=2;

[ma, na]=size(A);
[mc, nc]=size(C);

[mb, nb]=size(B);
X=zeros(mb, 1);
X=[If; Vs; Is; IL];

R=zeros(NP, 1);
R(:, 1)=Is_ref;

```

```

% UT=[-1 -1;-1 0;-1 1;0 -1;0 0;0 1;1 -1;1 0;1 1];
% UT=[-1 -1;-1 1;1 -1;1 1];
%J=zeros(3^NC,1);
UTLine=zeros(1,NC);
Y=zeros(NP,1);

J_global=2e10;
x_opt=x_opt_kml;
for j=1:5^NC
    UTLine=UT(j,:);
    UTLine=UTLine';
    Y=F*X+Phi*UTLine;

    %J=1*sum(abs(R-Y));
    J=1*sum(abs(R-Y));
    if(J<J_global)
        J_global=J;
        x_opt=j;
    end
end
U=UT(x_opt,1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%direct compute U
Phi_Phi=Phi'*Phi;
Phi_F=Phi'*F;
Phi_R=Phi'*R;
UT4=zeros(NC,1);
UT4=(Phi_Phi)\(Phi_R-Phi_F*X);

U1=UT4(1,1);
%%Set the control signal for the switches
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

end

```