

Analysis of a Dynamic Voltage Regulator

A Low voltage compensation circuit based on an AC chopper

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Abstract

Dynamic Voltage Regulator(DVR) based on a PWM controlled AC chopper is proposed in the present thesis. The DVR is suitable to settle the low-voltage problem at the terminals of the distribution system, especially in rural power networks. The AC buck chopper is composed of four self-turn-off devices and is controlled by the non-complementary method without current detection. The operation principle of the switches is pulse width modulation (PWM), and the duty cycle is adjusted according to the degree of voltage drop at the input line. The compensation device is connected to the power supply line in series and starts up when the line voltage drops. This device doesn't need any energy storage component and it only acts on the voltage difference. So the voltage rating can be kept low, which yields a low cost. Additionally it has a high reliability and wide compensation range. It is suitable for continuous voltage regulation and long time operation. The accuracy and availability of this solution is proved by the simulations.

Key words: power quality, dynamic voltage regulator, AC chopper, voltage compensation, pulse width modulation

Index

ABSTRACT	I
INDEX.....	II
FIGURES INDEX.....	IV
TABLES INDEX	VI
1. INTRODUCTION.....	1
1.1 DEVELOPMENT OF MODERN POWER ELECTRONICS.....	1
1.1.1 Problem on Power Quality.....	3
1.1.2 Classification of Power Quality Problems.....	4
1.1.3 The Influence of Power Quality Problem	5
1.2 VOLTAGE SAG AND SWELL	6
1.2.1 Definition.....	6
1.2.2 Characterization and Effect.....	6
1.2.3 Treatment.....	9
1.3 THE AIMS	9
2. DYNAMIC VOLTAGE REGULATOR.....	10
2.1 CONSTRUCTION OF VOLTAGE REGULATOR ^{[9] [10]}	10
2.1.1 Main Circuit.....	10
2.1.2 Energy Storage Unit	11
2.1.3 Inverter	12
2.1.4 Filter	13
2.1.5 Connecting type ^[12]	14
2.2 PRINCIPLE OF WORK ^[17]	16
2.3 CONTROL STRATEGY OF VOLTAGE COMPENSATION ^[14]	21
2.3.1 Reactive power compensation	22
2.3.2 In-phase compensation	22
2.3.3 Best quality compensation	22
2.3.4 Minimum power compensation	23

2.4	CONCLUSION	23
3.	CIRCUIT DESIGN.....	24
3.1	INTRODUCTION TO PSCAD.....	24
3.2	CIRCUIT	24
4.	EXPERIMENT AND SIMULATION	30
4.1	GENERAL SIMULATION RESULT.....	30
4.2	ADJUSTMENT AND ADVANCED EXPERIMENT.....	33
4.3	CONCLUSION	44
4.4	HARMONIC ANALYSIS.....	44
	ACKNOWLEDGEMENT	46
	REFERENCE	47

Figures index

Figure 1-1 Block diagram of a power electronic system	1
Figure 1-2 Regular power quality problem in Power system	4
Figure 1-4 Amplitude value of fundamental when unbalanced three-phases voltage sag happens	7
Figure 1-3 a) Three-phase balance voltage sag, b) six types of three-phase unbalance voltage sags	7
Figure 1-5 Amplitude value of fundamental when the induction-machine starts	8
Figure 2-1 Series and parallel connection DVR	10
Figure 2-2 Series and parallel connection DVR	11
Figure 2-3 Series DVR	11
Figure 2-4 Three typical inverters	13
Figure 2-5 Three locations of filter	14
Figure 2-6 System block diagram	16
Figure 2-7 AC chopper circuit structure	17
Figure 2-8 Gate pulses for the IGBTs using non-complementary control	17
Figure 2-9 Current path when P1, P2, P4 turn on and P3 turns off	18
Figure 2-10 Current path when P1, P2, P4 turn on and P3 turns off	18
Figure 2-11 Current path when P2, P4 turn on and P1, P3 turn off	19
Figure 2-12 Current path when P2, P4 turn on and P1, P3 turn off	19
Figure 2-13 Current path when P2, P3, P4 turn on and P1 turns off	20
Figure 2-14 Current path when P3, P4 turn on and P1, P2 turn off	20
Figure 2-15 Equivalent circuit of DVR	21
Figure 2-16 Compensation voltage vector	21
Figure 2-17 Compensation voltage vector	22
Figure 2-18 Compensation voltage vector	22
Figure 2-19 Compensation voltage vector	23

Figure 3-1 Whole view of Circuit	25
Figure 3-2 Block of power source	25
Figure 3-3 The impedance curve of Γ -type LPF	26
Figure 3-4 Filter circuit	28
Figure 3-5 Inverter unit	28
Figure 3-6 Actuating signal control.....	29
Figure 4-1 RMS value of voltage waveform	30
Figure 4-2 Zoom-in graph of system voltage usys.....	31
Figure 4-3 Compensation output voltage waveform	31
Figure 4-4 Load voltage waveform.....	32
Figure 4-5 RMS value of voltage waveform	32
Figure 4-6 Measuring point	33
Figure 4-7 comparison of voltage on different winding in normal size and in expanding view ...	34
Figure 4-8 comparison of voltage on S2 and primary winding in normal size and in expanding view	34
Figure 4-9 comparison of voltage on S1 and primary winding in normal size and in expanding view	35
Figure 4-10 comparison of voltage on S4 and primary winding in normal size and in expanding view	35
Figure 4-11 comparison of voltage on S3 and primary winding in normal size and in expanding view	36
Figure 4-12 comparison of voltage on resistance and primary winding.....	36
Figure 4-13 comparison of input voltage and voltage on primary winding in normal size and in expanding view	37
Figure 4-14 comparison of the peak value of input voltage and voltage in primary winding	37
Figure 4-15.....	38
Figure 4-16.....	38
Figure 4-17 comparison of input voltage Vac and output voltage in normal size and expanding view	39

Figure 4-18 comparison of input voltage Vac and output voltage in normal size and expanding view	40
Figure 4-19 Waveform when S3 or S1 turns off	40
Figure 4-20 Source voltage and its expanding graph	41
Figure 4-21 Input voltage and its expanding graph.....	41
Figure 4-22 Compensation voltage and its expanding graph.....	42
Figure 4-23 Load voltage and its expanding graph	42
Figure 4-24 General view and zoom-in view of waveform when S1 turns off	43
Figure 4-25 General view and zoom-in view of waveform when S2 turns off	43
Figure 4-26 General view and zoom-in view of waveform when S3 turns off	43
Figure 4-27 General view and zoom-in view of waveform when S4 turns off	44

Tables index

Table 1-1 Power Electronics Applications ^[1]	2
Table 1-2 Character and classification of electromagnetic phenomenon in IEEE standard ^[2]	4
Table 1-3 Definition of Different kinds of power quality problems	5
Table 4-1 Parameters	33
Table 4-2 Parameters	39
Table 4-3 Parameters	39
Table 4-4 Parameters	41

1. Introduction

1.1 Development of Modern Power Electronics

Usually, the devices of power electronics are mainly used for operating and controlling the flow of electric energy since it can detect the change of the voltages and currents and supply them in an optimal form that is suitable for user loads. Figure 1-1 shows a block diagram form of a typical power electronic system. Generally, the electric utility provides the power input to the power processor, at a line frequency of 50 or 60 Hz, single phase or three phases. The power processed output, such as voltage, current, frequency, and the number of phases, is given by the power processor, although the case to determine it should be the load. In this case, a feedback controller will be installed at the output side of the power processor to compares the power output with a reference (or desired) value and it also will reduce the error between two values to a minimum rate.

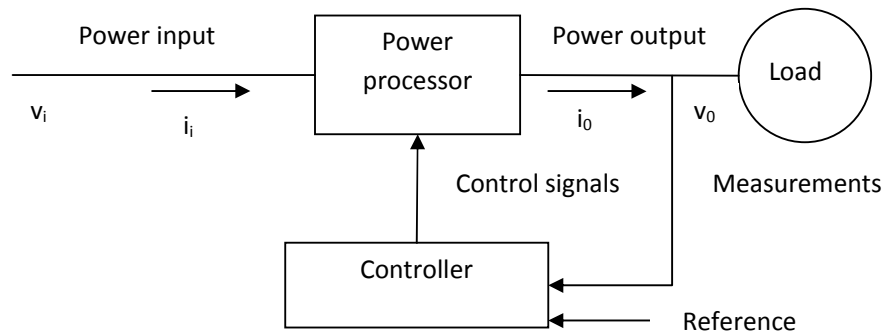


Figure 1-1 Block diagram of a power electronic system

The traditional knowledge of power electronics is based on low frequency technology. With a large growth in the field of power electronics which has been experienced in recent years, high frequency technology is used for modern power electronics nowadays. Table 1-1 lists various applications that cover a wide power range from a few tens of watts to several hundreds of megawatts. As power semiconductor devices improve in performance and decline in cost, more systems will undoubtedly use power electronics.

1. Introduction

(a) Residential	(d) Transportation
Refrigeration and freezers	Traction control of electric vehicles
Space heating	Battery chargers for electric vehicles
Air conditioning	Electric locomotives
Cooking	Street cars, trolley buses
Lighting	Subways
Electronics (personal computers, etc.)	Automotive electronics including engine control
(b) Commercial	(e) Utility systems
Heating, ventilating, and air conditioning	High-voltage dc transmission (HVDC)
Central refrigeration	Static var compensation (SVC)
Lighting	Supplemental energy sources, fuel cells
Computers and office equipment	Energy storage systems
Uninterruptible power supplies (UPSs)	Induced-draft fans and boiler feed water pumps
Elevators	Dynamic voltage regulator (DVR)
(c) Industrial	(f) Aerospace
Pumps	Space shuttle power supply systems
Compressors	Satellite power systems
Blowers and fans	Aircraft power systems
Machine tools (robots)	
Arc furnaces, induction furnaces	
Lighting	
Industrial lasers	
Induction heating	
Welding	
	(g) Telecommunications
	Battery chargers
	Power supplies (dc and UPS)

Table 1-1 Power Electronics Applications^[1]

1.1.1 Problem on Power Quality

Industrial and commercial consumers of electrical power are more and more sensitive to the quality of the electrical power supply. In another words, the power quality and reliability issues are the master keys to delivery energy successfully and accurately. Generally, power blackouts and brownouts often have serious economic consequences. Poor power quality also causes a non-ignorable impact on computers and other sensitive equipments. Meanwhile, with the growth of international terrorism, security should be considered as an indispensable role. Table 1-2 lists a classification of electromagnetic phenomena in the field of power quality.

Category			Frequency spectrum	Duration	Voltage magnitude
Transient phenomenon	Impulse	ns	5ns rise	<50ns	
		μ s	1 μ s rise	50ns-1ms	
		ms	0.1ms rise	>1ms	
	Oscillation	LF	<5kHz	0.3~50ms	0~4pu
		MF	5~500kHz	20 μ s	0~8pu
		HF	0.5~5MHz	5 μ s	0~4pu
Short-period variation	Instant	break		0.5~30T	<0.1pu
		sag		0.5~30T	0.1~0.9pu
		swell		0.5~30T	1.1~1.4pu
	Transient	break		30T~3s	<0.1pu
		sag		30T~3s	01.~0.9pu
		swell		30T~3s	1.1~1.4pu
	Short time	break		3s~1min	<0.1pu
		sag		3s~1min	0.1~0.9pu
		swell		3s~1min	1.1~1.2pu
Long-period variation	Continuously break			>1min	0pu
				>1min	0.8~0.9pu

1. Introduction

	Undervoltage		>1min	1.1~1.2pu
	Overvoltage			
Imbalance voltage			Steady state	0.5%~2%
0%~0.1%	DC offset		Steady state	0%~0.1%
	Harmonics		Steady state	0%~20%
	Inter-harmonics	0~6kHz	Steady state	0%~2%
	Trapping wave		Steady state	
	Noise	Broad band	Steady state	0%~1%

Table 1-2 Character and classification of electromagnetic phenomenon in IEEE standard^[2]

And Figure 1-2 shows the sketch graph of dynamic power quality.

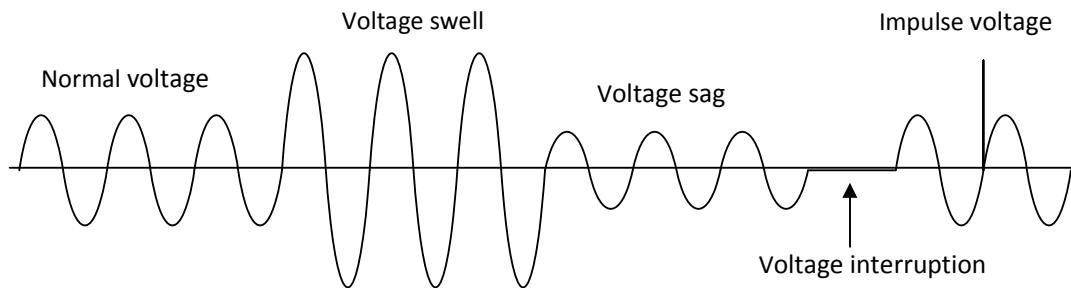


Figure 1-2 Regular power quality problem in Power system

1.1.2 Classification of Power Quality Problems

The technical terms and definitions of power quality problems are shown in the table 1-3.

Technical terms	Definition
Voltage sag	A brief reduction in voltage under rated frequency, typically lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds.
Voltage swell	A brief increase in voltage under rated frequency, typically lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds.

1. Introduction

Interruption	A loss of voltage in one phase or three phase. A transient interruption lasts from a cycle to 3 seconds, a short-time interruption lasts from 3 seconds to 60 seconds, a long-term interruption lasts longer than 60 seconds.
Transient voltage	A transient variation of the voltage magnitude between two steady state buses. Generally, it's an impulse in one phase during transient state.
Harmonic	In acoustics and telecommunication, a harmonic of a wave is a component frequency of the signal that is an integer multiple of the fundamental frequency. Harmonic frequencies are equally spaced by the width of the fundamental frequency and can be found by repeatedly adding that frequency.
Fluctuation	Random variations of the magnitude of the voltage. Generally, the variation is from 0.9p.u to 1.1p.u
Unbalance voltage	The ratio between the maximum voltage excursion and the mean value of three phase voltage.
Overvoltage	An increase in voltage, lasting more than 60 seconds.
Undervoltage	A reduction in voltage, lasting more than 60 seconds.

Table 1-3 Definition of Different kinds of power quality problems

1.1.3 The Influence of Power Quality Problem

Power quality problem are definitely harmful for both the power system and customers. And the influences of it are including:

- 1) Additional loss of power system device reduces the efficiency and operating life of the generating equipment, transmission line and electrical equipment.
- 2) It produces mechanical vibration, noise and overvoltage, which results in overheat in some part of transformer.
- 3) The false tripping of relay protection and automation device would increase, and it could cause an inaccuracy measurement of electric testing instrument.
- 4) A disturbance on telecommunication system nearby could produce noise and interfere the communication quality, or sometimes it could cause message dropping.
- 5) The harmonic causes overheat, ageing of insulation, life-span shortening and damages in capacitor and transmission line.
- 6) The harmonic also causes parallel resonance and series resonance in part of power system, which enlarge the harmonic all the more. The harmful could be to a higher degree, and sometimes a major accident will take place.
- 7) A voltage imbalance leads to a zero potential drift, which influences the work of computers.

1.2 Voltage Sag and Swell

A rough statistics suggests that about 92% of the interruptions in industrial installations are voltage sag related.^[3] And in most cases, the problem is caused by remote faults or changes in the loading condition.

1.2.1 Definition

The voltage sag as defined by IEEE standard 1159-1995, IEEE Recommended Practice for Monitoring Electric Power Quality, is: “a brief reduction in voltage, typically lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds.” To the contrary, voltage swell is a brief increases in voltage over the same time range. But a low or high voltage last in longer periods is referred to as “undervoltage” or “overvoltage”.

The voltage sag/swell lasts just as little as a few cycles, but it can also affect some certain sensitive loads, such as adjustable speed drives (ASD) and programmable logic controllers (PLC).

1.2.2 Characterization and Effect

Voltage sag

The causes for voltage sags are abrupt increases in loads, such as disturbances, induction-machine starting, electric heaters turning on, or an unplanned increase in source impedance caused by a loose connection, etc. On the contrary, voltage swells are almost always caused by an abrupt reduction in loads, such as a poor or damaged voltage regulator. Besides all, they can also be caused by a damaged or loose neutral connection.^[4]

Based on symmetrical components, the voltage sag type indicates which phases are involved in the event. Figure 1-3 gives a basic type of balanced voltage sag and six types of unbalanced voltage sags.

Balanced voltage sag (type A) is due to an equal drop in the values of voltage in three-phases. Unbalanced voltage sag (types B and C) is due to a drop between two phases or a drop in one phase.^[5]

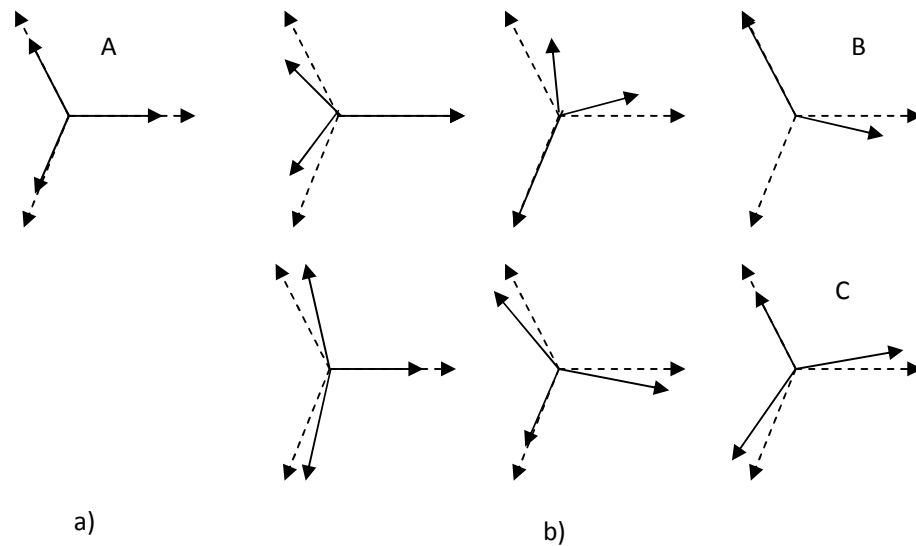


Figure 1-3 a) Three-phase balance voltage sag, b) six types of three-phase unbalance voltage sags

Actually, the voltage sag is classified from several different causes:^[6]

1) Voltage sag caused by disturbance

The magnitude and phase angle of the voltage sag is determined by the type and the position of the disturbance. And the lasting time of the voltage sag depends on the protect way. Both balanced and unbalanced voltage sag could appear in this case.

In figure 1-4, the amplitude value of fundamental of voltage sag is shown when a disturbance occurs in the 110kV power system. Seen from the graph, the magnitudes of the fundamental voltage are rectangular, and they are different in different phase, since it is caused by an unbalanced disturbance.

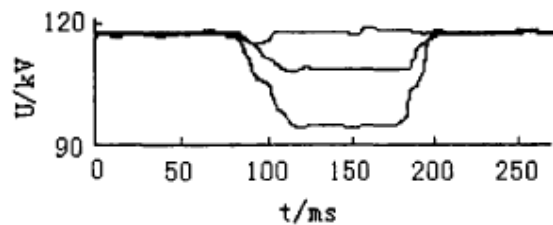


Figure 1-4 Amplitude value of fundamental when unbalanced three-phases voltage sag happens

2) Voltage sag caused by large induction-machine starting

When the induction-machine starts, the starting current could be 5~10 times of the normal value in steady state, and the power factor will be low. Voltage sag will be caused by this high

starting current, and the magnitude of it depends on the characteristic of the induction-machine and the short-current capacity of the system.

The figure 1-5 shows the amplitude value of fundamental when the induction-machine starts. The magnitude of three-phase fundamental voltage decreases at the beginning, and then it recovers since the current return to the normal value.

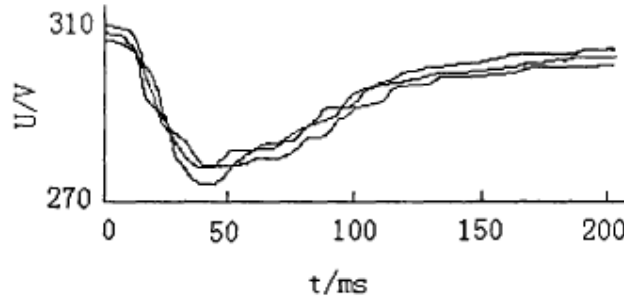


Figure 1-5 Amplitude value of fundamental when the induction-machine starts

3) Voltage sag caused by excitation flow of transformer

A large impulse current will be generated when the transformer injects to the power system with no-load. The relationship among transient magnetic flux ϕ , static maximum main magnetic flux ϕ_m and input initial phase angle α is derived in equation 1-1.

$$\phi = \phi_m \cos \alpha + \phi_m \cos(\omega t + \alpha) \quad (1-1)$$

Seen from the equation, the maximum value of transient main magnetic flux could be twice as the value in static when the initial phase angle input as zero. Considering the residual magnetism, it will reach to 2.3 times. Since the iron core is saturated when the transformer runs normally, the excitation current could reach to several ten times of regular value. And it is so enough to cause voltage sag.

Voltage swell

Voltage swell is less common than voltage sag, but it's also usually associated with system fault conditions. A swell can occur due to a single line-to-ground fault on the system, or it can also be generated when there is an unplanned load decrease.

- 1) Usually in ungrounded or floating ground Delta systems, the single line-to-ground fault could result in a temporary voltage rise on the unfaulted phases. The value of the line-to-ground voltages will be rise to 1.73pu during the fault condition.
- 2) A sudden load decrease could cause an abrupt interruption of current, and a large voltage will be generated in that case. And switching on a large capacitor bank also could cause a swell, though it more often causes an oscillatory transient.^[4]

1.2.3 Treatment

Several ways to correct the voltage sag/swell are commonly used nowadays.^[7]

- 1) Uninterruptable Power Supply (UPS)
A continuous power supply will be used during the period of voltage sag/swell in high efficient as 92%~97%. An expensive expense and restricted capacity is the disadvantage of UPS.
- 2) Constant Voltage Transformer (CVT)
It's generally used under 20kVA power system. A balanced voltage will be supplied even the voltage drops to the 70% of normal value. And its efficient is between 70%~75%.
- 3) Static Transfer Switch (STS)
It's set in a dual-power system. When one of the power supplies has problem, the STS will switch to another one as the power supply for the load.
- 4) Transformer Tap-Change (TC)
It can reduce the effect of voltage sag/swell during a certain extent, which is determined by the adjusting range of the tap changer.
- 5) Motor-Generator (MG)
The inertia of the motor could be used to keep the normal voltage when the voltage sag/swell happens.
- 6) Dynamic Voltage Regulator (DVR)
It's the cheapest device according to the other ones. It has a high efficient, since the DVR only works when the voltage sag/swell happens.

1.3 The aims

Due to the excellent dynamic performance of the Dynamic Voltage Regulator it is the most efficiency solution dealing with the dynamic voltage problem. Additionally, the large capacity of the DVR makes it as an economic method also.

The analysis of DVR will be performance in several divisions during the following work:

- 1) Construction, operation principle of DVR
An overall presentation of the whole system and some detailed description of each component will be given in the second chapter.
- 2) Corresponding circuit design of DVR
To use PSCAD to organize an AC buck chopper circuit that is corresponding to the DVR.
- 3) Simulation
Some simulations and comparisons will be given in the forth chapter.

2. Dynamic Voltage Regulator

2.1 Construction of Voltage regulator [9] [10]

The Dynamic Voltage Regulator consists of several parts. Besides of the structure, the control strategy is also an important thing to consider. In this section, the construction a DVR and some regular control strategies for it will be introduced.

2.1.1 Main Circuit

A typical DVR is formed by four devices: Energy Storing Device, Inverter, Filter and Series Transformer.

Figure 2-1 shows the construction of a series DVR and the connecting way of it rated to the transmission system. Actually, the series transformer is not necessary in some cases. In low-voltage distribution, the normal frequency transformer is often used in the DC bus bar side to insulate the DC bus bar apart from the power system.

Figure 2-2 shows a construction of a DVR without a series transformer. The magnitude of the DC voltage can be adjusted by changing the ratio of the parallel connection transformer.

Figure2-3 is the series-DVR structure which has a DC energy storage to compensate the voltage sag (This type is usually called Dynamic Voltage Restorer). ^[11]

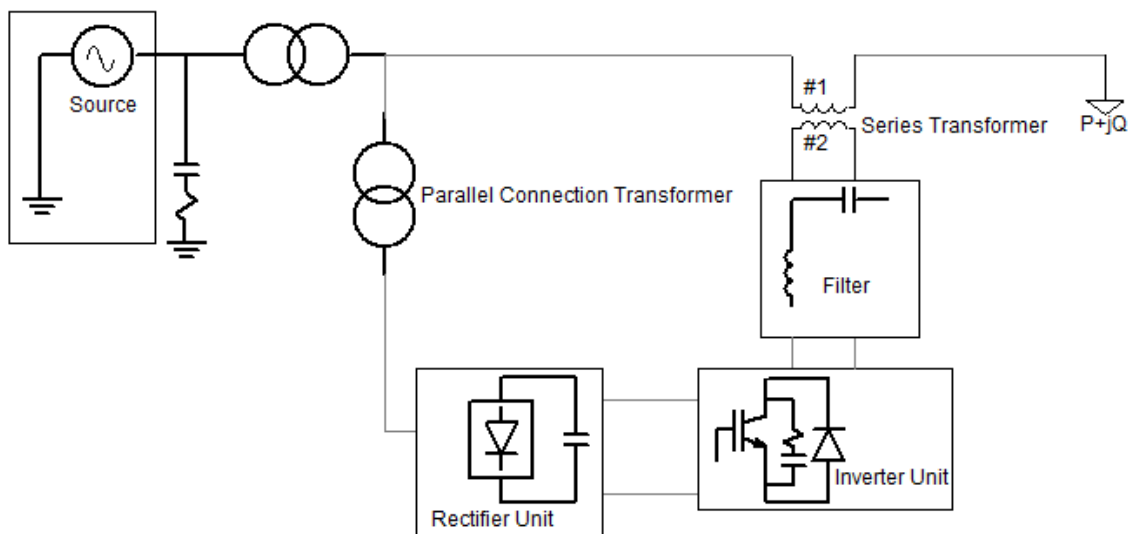


Figure 2-1 Series and parallel connection DVR

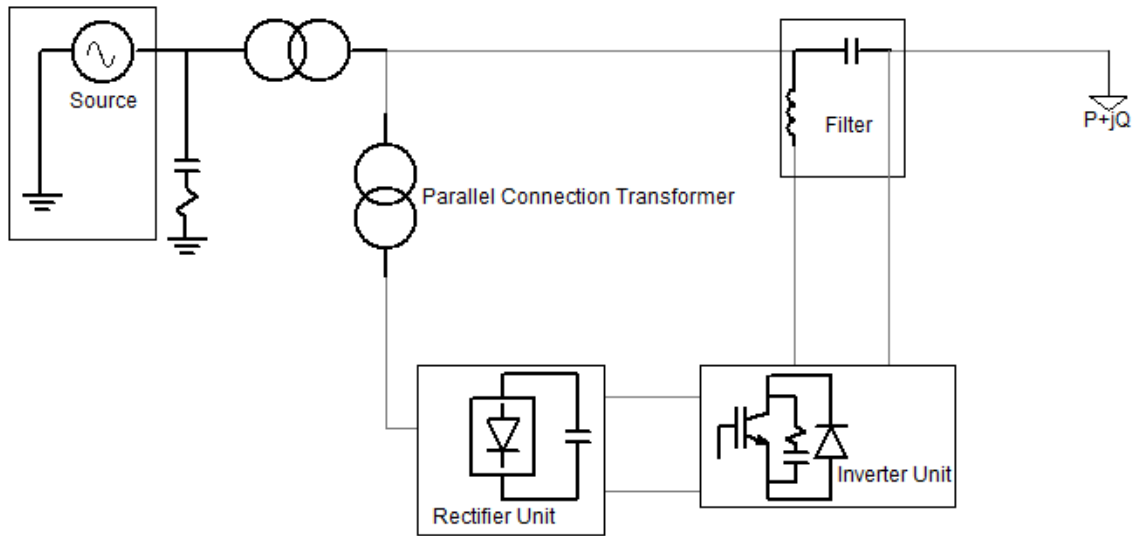


Figure 2-2 Series and parallel connection DVR

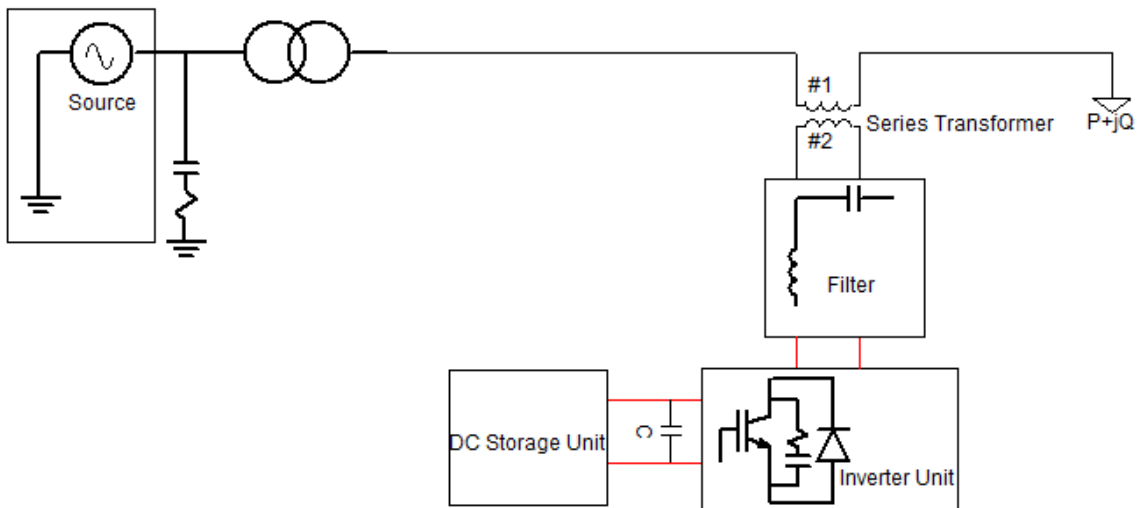


Figure 2-3 Series DVR

2.1.2 Energy Storage Unit

The energy unit is the power source of the DVR. The required energy that is supplied to the power system is provided by it. Generally, there are several types of energy storage units:

1) Accumulator cell

An accumulator cell not only provides reactive power adjusting, but also provides active power supply. And it can continue to supply the device when the power system is blackout for a short time, performing as an UPS. But an accumulator cell could only provide a short time compensation because of its capability limit. Furthermore it's expensive and it needs maintenance, which leading to an increase of the cost of DVR.

2) Energy supply by power system through Non-controlled rectifier

A rectifier energy supply system could work continuous in a long period. But the main defect is that the energy only has an one-way flow from system to the capacitor. So when voltage swell occurs, the DC voltage will increase sharply.

3) Energy supply by power system through controlled rectifier

The main improve is to solve the one-way flow problem. But a more complicated system needs more complex control strategy and increases the cost of DVR.

4) Other types

Superconductivity energy supply has high efficiency of energy transformation, and the response time is very short. Moreover, it is easy maintenance and it has no power pollution to the system. But such technique is still immature now, and the research on it will be continuing.

2.1.3 Inverter

The inverter is used to produce a compensation voltage into the power transmission line. Generally, it has several kinds of structure, such as semi-bridge, full-bridge and push-pull. In DVR design, the full-bridge inverter is the mostly used. It could compensate the zero sequence voltage, and it is easy to control. However, it has the bridge-arm shoot-through problem. Therefore, when such kind of structure is used, a reliable bridge-arm protection must be supplied.

The main advantage of the push-pull inverter is that, at any moment there is no more than one switching device operating. This means that the bridge-arm shoot-through problem eliminated. However, the voltage rating of the switch is twice of the capacitor voltage. So it is more suitable for a high power converter.

Figure 2-4 shows examples of typical half bridge, full bridge and push-pull inverters for DVRs,

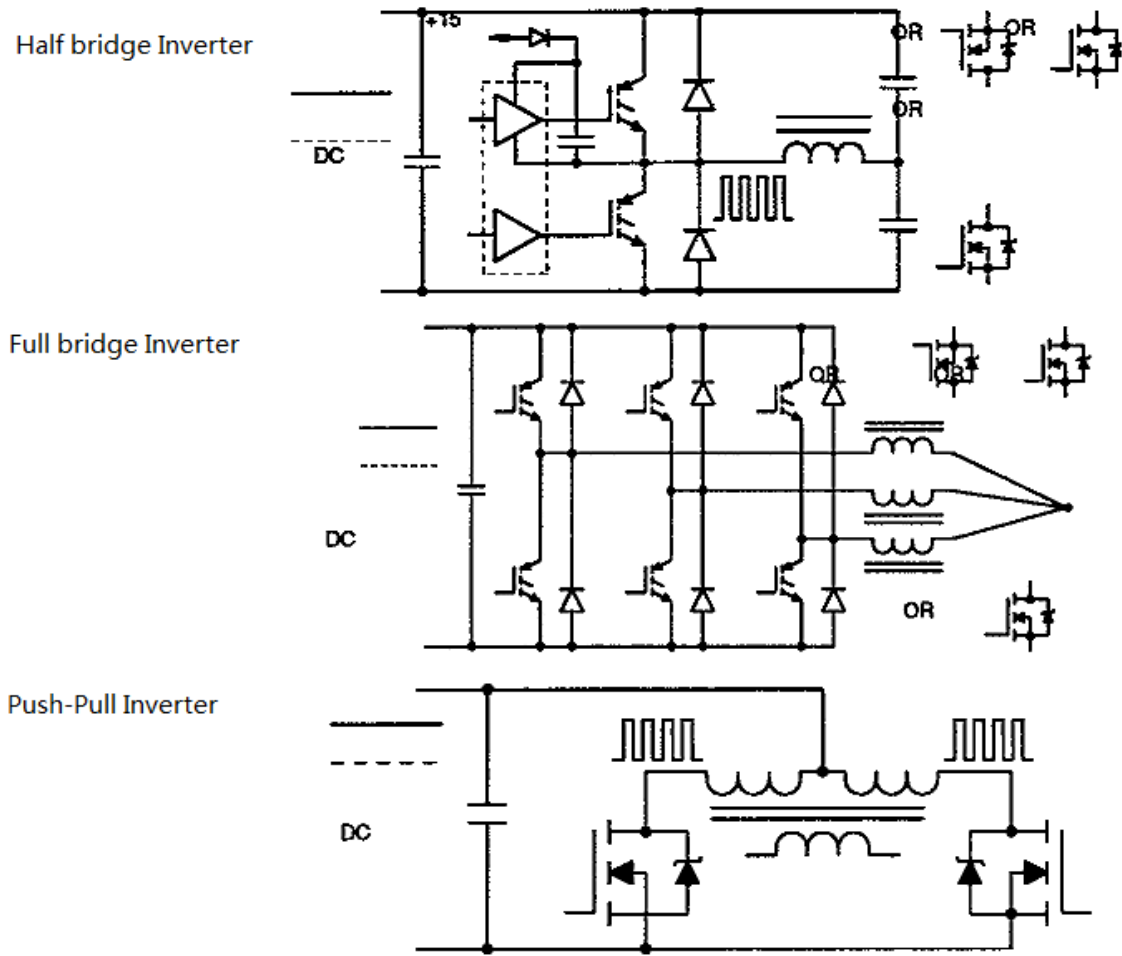


Figure 2-4 Three typical inverters

2.1.4 Filter

The inverter also produces harmonics into the circuit. Therefore, a filter is installed to eliminate the harmonics. And the inverter in different locations could give different influence on the DVR.

Figure 2-5 shows three different location of inverter in a DVR.

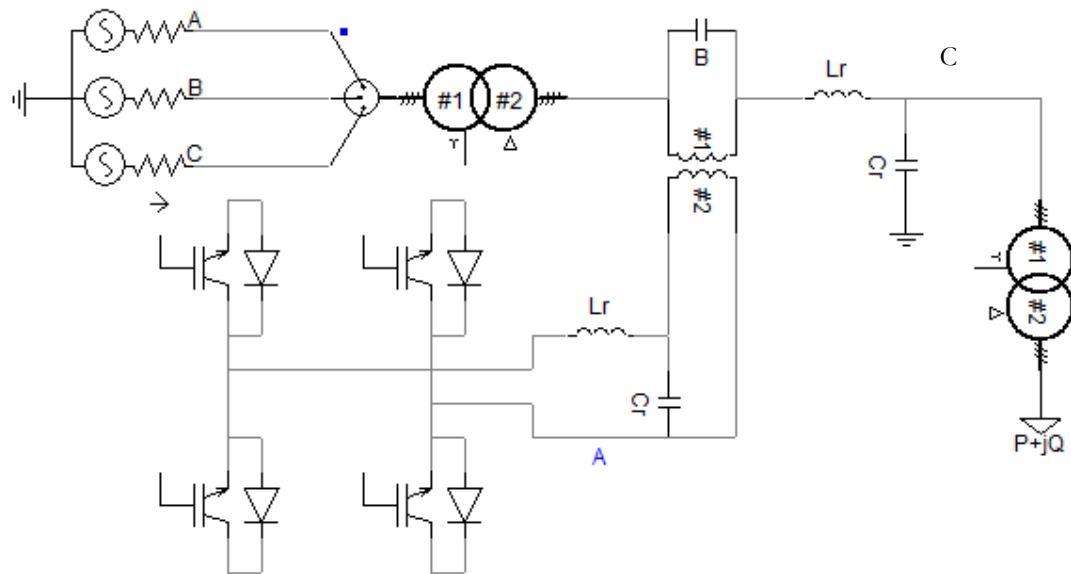


Figure 2-5 Three locations of filter

In position A, the inverter side, the filter could reduce the design capacity of the series transformer. Because the filter could shield higher harmonics of the compensation voltage supplied from inverter.

In position B, the line side, filter inductance could be reduced since the inductance leakage of transformer could be used as a filter inductance. In this case, the series transformer needs to deal with the power from higher harmonics, so the capacity of it definitely will increase.

In position C, the structure of filter changes a bit. The main advantage of it is the filter inductance could be used to eliminate the influence of the inductance leakage of transformer. But the high frequency current will flow into system current, which is the main defect.

2.1.5 Connecting type ^[12]

1) Series Transformer

The regular way is to connect a transformer between DVR and the transmission line. The first advantage is that the voltage on filter DC side could be much lower than that of the transmission line. The step-up transformer is able to be installed in this way. So the reliability of DVR is able to be enhanced when the voltage on the transmission line is high. The other advantage is the inverter and the power system is separated. So the WB of inverter is able to be get from high voltage rectifier.

However, since the transformer is a non-linear device, it will introduce some disadvantages indeed.

Firstly, high-frequency harmonics from the inverter causes difficulties in the transformer design. In this case, a higher capacity transformer must be used. Sometimes a filter at the output could be installed to solve the problem, but it will increase the cost of system significantly. Furthermore, especially in high voltage and high capacity systems, the design of such a filter is very difficult.

Secondly, the influence between series transformer and L-C filter certainly will bring an additional phase shift and voltage sag. Using a closed-loop voltage control is one way to solve the problem, but it also will increase the complexity of the control.

Thirdly, the introduction of a transformer obviously increases the cost of the system.

In conclusion, a usage of series transformer needs to consider all kinds of factors and the particulars of the power system in practical. Especially when it comes to a high-voltage power system, the series transformer is the preferable choice after considering the DVR structure, the DC-link voltage, and the cost of the devices.

2) Capacitance^[13]

In low-voltage power systems, a transformerless structure usually applies. Figure 2-2 shows a structure of this kind. When there is no series transformer, the DC side of the inverter must be separated from the power system. A power transformer is often installed to achieve such separation.

2.2 Principle of Work ^[17]

The system block diagram of an AC buck chopper with PWM control is shown in figure 2-6. When the bypass switch is closed the AC buck chopper is not operated. If the load voltage is lower than the threshold, the bypass switch opens and the device starts immediately. The output voltage of the AC chopper will add to line voltage thus increasing the load voltage to the rated voltage.

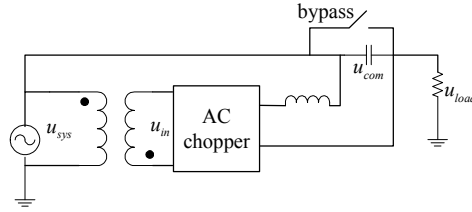


Figure 2-6 System block diagram

Let u_{in} be the transformer output u_{com} is the circuit output, u_{load} is the load voltage, n is the turns ratio of transformer, and D is the duty cycle. So the value of u_{load} could be derived by the equations 2-1 to 2-3.

$$u_{in} = \frac{u_{sys}}{n} \quad (2-1)$$

$$u_{com} = Du_{in} \quad (2-2)$$

$$u_{load} = u_{sys} + u_{com} \quad (2-3)$$

⇒

$$u_{load} = u_{sys} \left(1 + \frac{D}{n}\right) \quad (2-4)$$

As shown in the formula, to stabilize the load voltage u_{load} , the duty cycle D should change according to the system voltage u_{sys} . And the compensation voltage u_{com} has the same phase angle as u_{sys} , so the way of compensation is magnitude compensation.

Figure 2-7 is an AC buck chopper's circuit structure. The AC capacitor C1 is used for providing reactive power, so as to maintain voltage at secondary side of transformer. P1, P2, P3, P4 were IGBT with freewheeling diode, L and C2 made up passive filter.

2. Dynamic Voltage Regulator

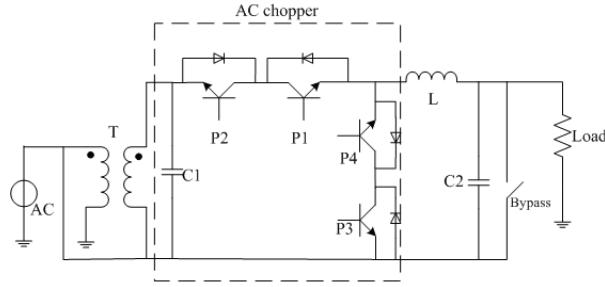


Figure 2-7 AC chopper circuit structure

This circuit operates under the strategy of non-complementary control without current detection. During the positive half cycle, P1 and P3 are closed in turns while P2 and P4 are kept closed. On the contrary, in negative half cycle P2 and P4 are closed in turns while P1 and P3 are kept closed.^[19]

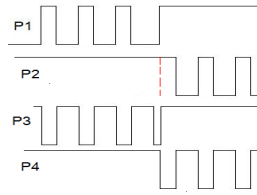


Figure 2-8 Gate pulses for the IGBTs using non-complementary control

Through closed-loop feedback, the duty cycle changes according to the degree of voltage drop at system network. The difference between u_{load} and 220V is the necessary compensation voltage. D is defined as:

$$D = \frac{220 - u_{load}}{u_{in}} \quad (2-5)$$

P1~P4 are controlled with PWM according to D . Then the output voltage of this circuit is adjusted smoothly.

The topological modes are classified into active mode, dead time, and freewheeling modes. The inductor current flows through the voltage source during the active mode. The current direction is shown in figure 2-9 and 2-10.

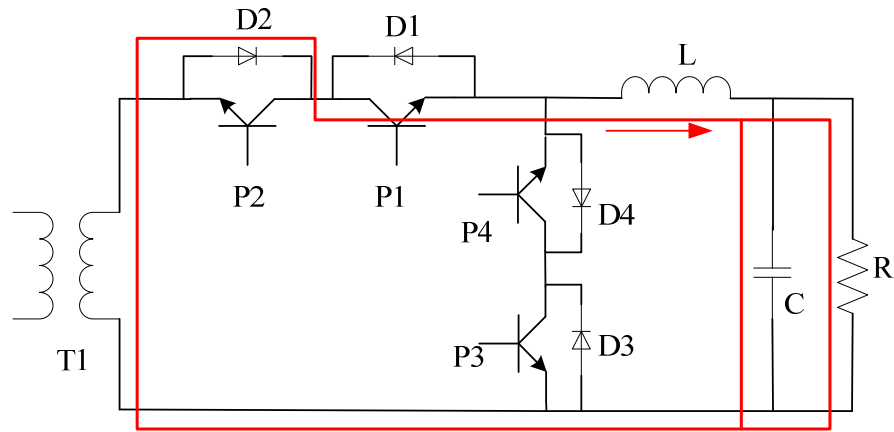


Figure 2-9 Current path when P1, P2, P4 turn on and P3 turns off

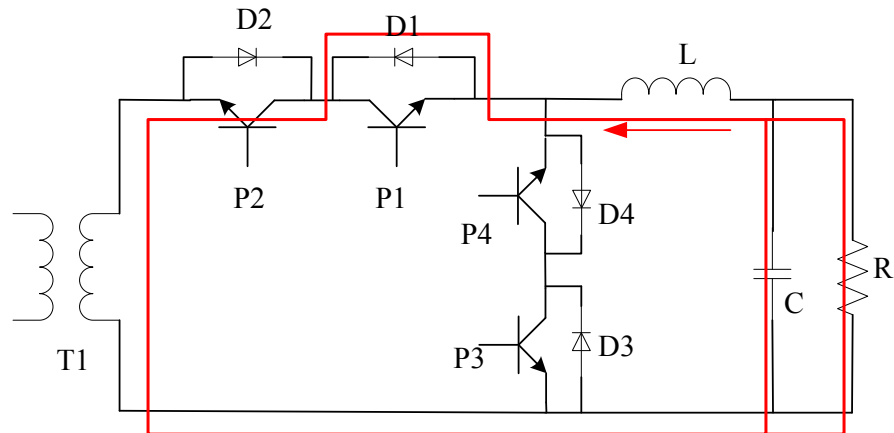


Figure 2-10 Current path when P1, P2, P4 turn on and P3 turns off

2. Dynamic Voltage Regulator

Then two modulated switches are turned off, the circuit comes in to dead-time mode. The current path is shown in figure 2-11 and 2-12.

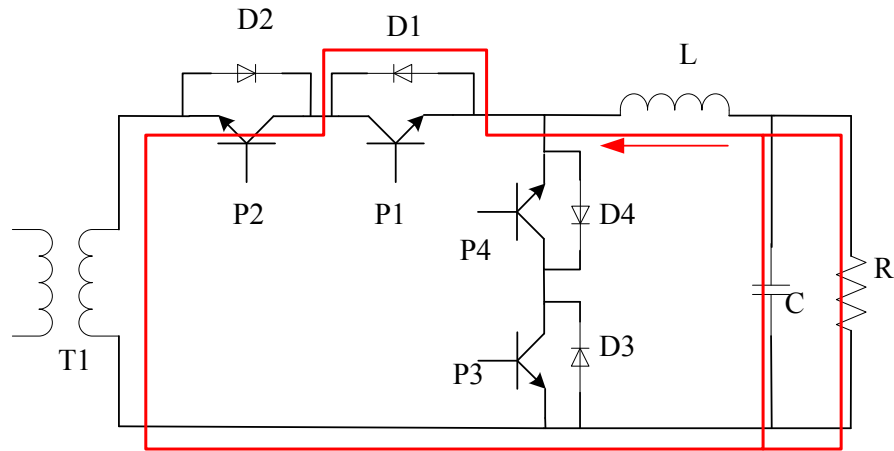


Figure 2-11 Current path when P2, P4 turn on and P1, P3 turn off

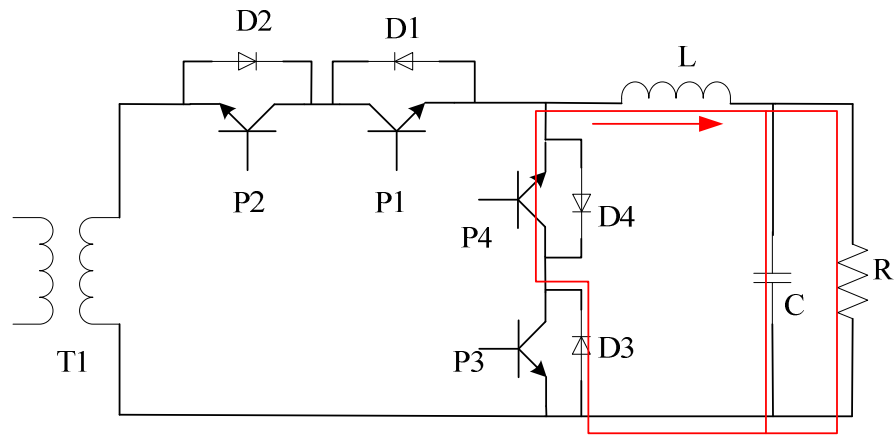


Figure 2-12 Current path when P2, P4 turn on and P1, P3 turn off

2. Dynamic Voltage Regulator

In the freewheeling mode, the inductor current freewheels through the switch P3 and P4, as shown in figure 2-13 and figure 14.

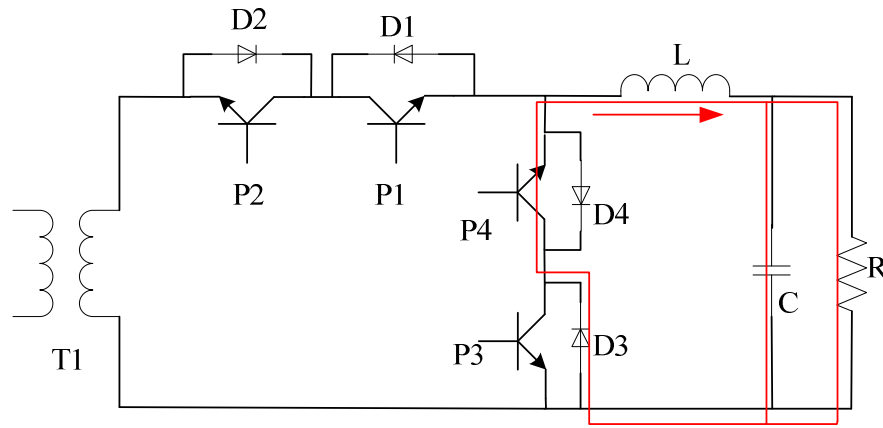


Figure 2-13 Current path when P2, P3, P4 turn on and P1 turns off

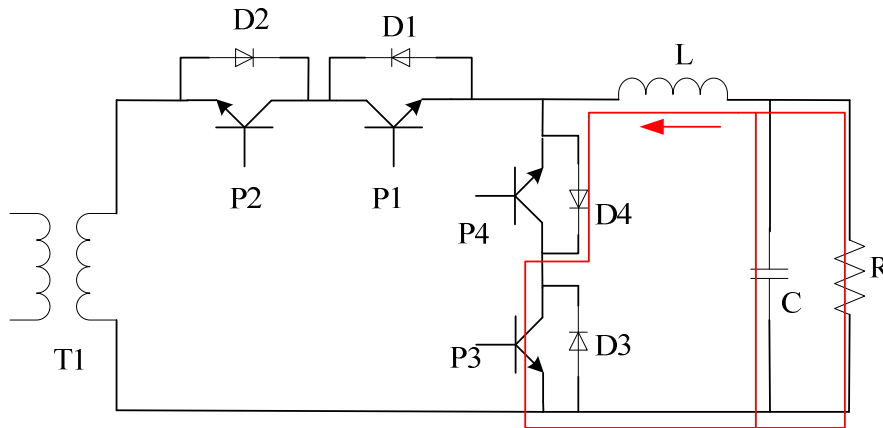


Figure 2-14 Current path when P3, P4 turn on and P1, P2 turn off

2.3 Control Strategy of Voltage Compensation ^[14]

An introduction of DVR is corresponding to series a controlled voltage source between generator and load. And the voltage supplied from controlled voltage source eliminates the distortion of system voltage.

In this case, figure 2-15 and figure 2-16 show an equivalent circuit and compensation voltage vector graph. Where U_s stands by the source voltage, U_c is the compensation voltage and U_L is the load voltage. Z_s and Z_L are the impedances of the power source and the load.

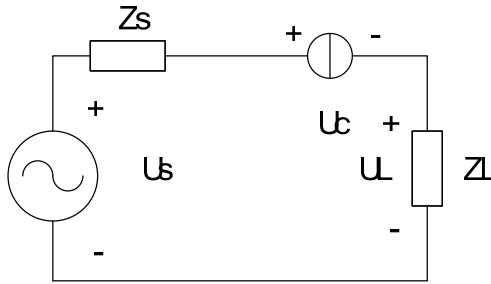


Figure 2-15 Equivalent circuit of DVR

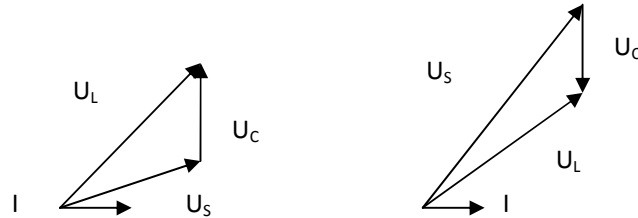


Figure 2-16 Compensation voltage vector

Seen from the figure, when U_s is fix, different load voltage U_L is able to get by adjust the output compensation voltage U_c from DVR. And the maximum voltage compensation from DVR and the capacity of energy storage in DC-link voltage unit is two main targets to determine the cost of DVR. Then different control strategies are under consideration to minimum the capacity of energy storage and meanwhile to maximum the compensation voltage. In this case, according to different control strategy, the way for voltage compensation could be divided into the following categories.

2.3.1 Reactive power compensation

In this case the DVR could not provide active power compensation to a DC-link voltage unit, but it could compensate reactive power. So the compensation voltage U_c keeps vertical to load current I_L . In figure 2-17, U_s and U_L are the voltage in system side and voltage in load side when the sag occurs, U_c is the compensation voltage, U is the system voltage in nominal condition, φ is the power coefficient angle of the load, α is the phase trip angle when sag occurs, and θ is the power coefficient angle of the compensation output. And in this case, $\theta=90^\circ$.

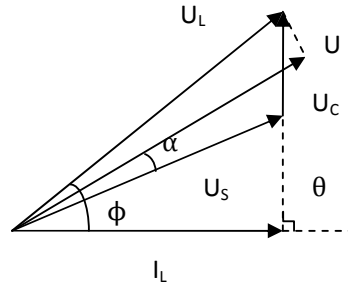


Figure 2-17 Compensation voltage vector

2.3.2 In-phase compensation

The compensation voltage U_c has the same phase angle as the system voltage U_s . In figure 2-18, $\theta=\theta$, so the magnitude of compensation voltage output from DVR is minimum. And both active power and reactive power are compensated in this way.

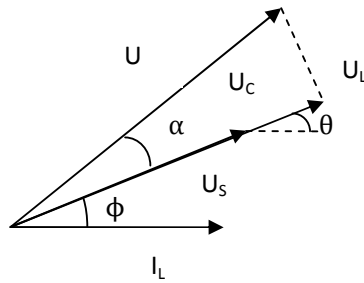


Figure 2-18 Compensation voltage vector

2.3.3 Best quality compensation

The magnitude and phase angle of load voltage are compensated to the same as before the sag occurs. It is suitable for the sensitive load, which has a strict quality demand in voltage magnitude and phase angle. And figure 2-19 shows the vector graph. Also both active power and reactive power are compensated in this way.

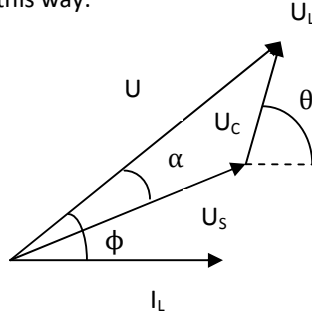


Figure 2-19 Compensation voltage vector

2.3.4 Minimum power compensation

Two ways mentioned above, which are able to compensate both active power and reactive power, have demanding in active power supply of DC-link voltage unit. And the output energy of both of them are not able to control. So when the voltage swell occurs, the energy might be backward. And it will cause a boost arise of DC capacitor voltage.

As a result, the way to minimum power compensation is brought forward. And the active power output is $P = U_c \times I_L \times \cos \theta$. Since the DVR is series connection between generator and load, it has the same current as the load current I_L . So in order to reduce the active power output P , the magnitude of compensation voltage U_c should reduce or the power coefficient angle θ should increase. And the way to realize minimum power compensation is to force the output voltage vector being vertical to the load current by change the phase angle between output voltage and load current. At this moment, the output active power from DVR is minimised. So in another saying, the way of reactive power compensation is a particular case of minimum power compensation.

2.4 Conclusion

- 1) Description on the main structure of DVR, and comparison between the series transformer connecting way and non series transformer connecting way are given in this section. And the position where the filter unit is switched in is discussed also.
- 2) The principle and the course of the work of DVR is explained. The AC buck chopper's circuit structure is described and analysis in detail.
- 3) Four different voltage compensation strategies are explained: reactive power compensation, in-phase compensation, best quality compensation and minimum power compensation.

3. Circuit Design

The circuit of DVR is formed in PSCAD software. And the simulation should be given in specified environment. Especially, the influence of the modules should be consider, and the experiment will be given based on it.

3.1 Introduction to PSCAD

PSCAD(Power System Computer Aided Design) is a popular software for power system design and simulation. It was developed by Dr. Dennis Woodford since year 1976. It is the pre-processing program of EMTDC(Electro Magnetic Transient in DC System). The customers could form electrical circuit, input the parameter of each component and compile by the FORTRAN compiler. The result is able to display in PLOT windows along with the working procedure. Besides all, PSCAD has an interface with MATLAB, and the latest version is PSCAD 4.2.^[20]

3.2 Circuit

A whole view of the circuit designed is shown in figure 3-1. It is including a controllable power source, an isolating transformer, a typical load system, a controllable filter circuit, an inverter unit and a compensation voltage source. And some oscillographs are including in the circuit also.

There is a conductance parallel connecting with the input voltage, which is used for compensating the reactive power. The value is 25 μ F, and it's an experience value. And more detailed description will be given in the following text.

3. Circuit Design

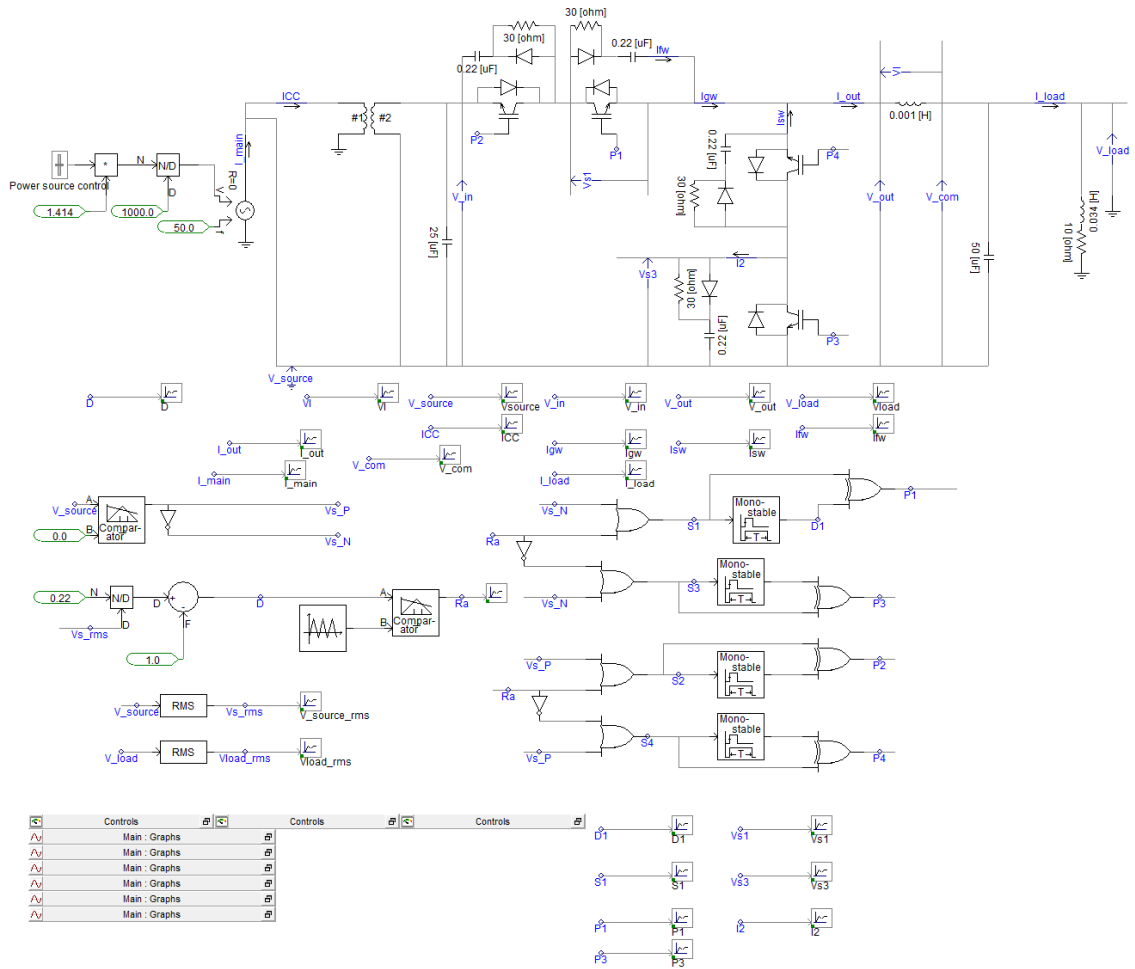


Figure 3-1 Whole view of Circuit

The power source is controllable, and the variation range is from 150V to 200V. And it's RMS value. For an ideal simulation, the resistance is set as zero, and frequency is 50Hz. Figure 3-2 shows the part of power source.

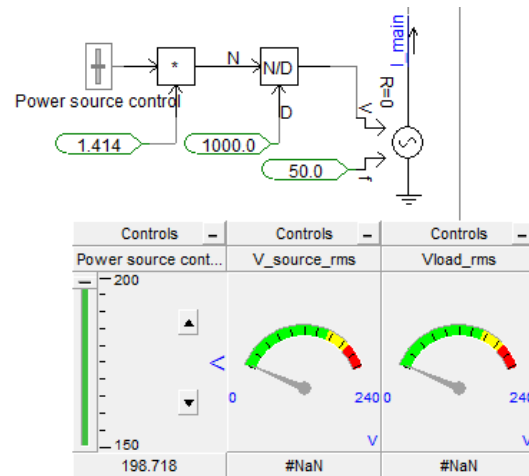


Figure 3-2 Block of power source

For the filter, the most important thing is to calculate the value of filter inductance and conductance. For a buck type AC choppers LPF, the curve of impedance is shown in figure 3-3. $X_L = \omega L = 2\pi fL$, it increases along with the increase of frequency. $X_C = \frac{1}{\omega C} = \frac{1}{2\pi fC}$, it decreases along with the increase of frequency.^[18]

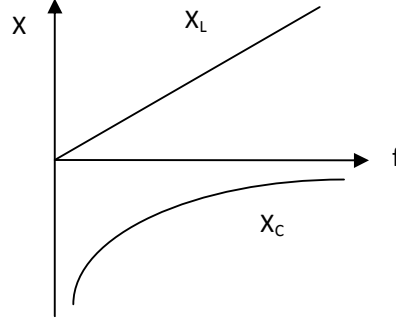


Figure 3-3 The impedance curve of Γ -type LPF

Since the frequency in the formula of X_L and X_C are the same cut-off frequency f_c , the relationship among them is shown in the equations 3-1, 3-2 and 3-3.

$$\omega_c L = 1/\omega_c C \quad (3-1)$$

$$\omega_c^2 = 1/LC \quad (3-2)$$

$$f_c = 1/2\pi\sqrt{LC} \quad (3-3)$$

The fundamental element of the capacitor output voltage U_{of} is derived by

$$U_{of} = \frac{-jX_C R_o}{X_C X_L - j(X_C - X_L)R_o} U_{rf} \quad (3-4)$$

Where, $U_{rf} = DU_s$

If $X_C \square R_o \square X_L$,

$$U_{of} = \frac{X_C R_o U_{rf}}{\sqrt{(X_C X_L)^2 + [(X_C - X_L)R_o]^2}} U_{rf} \square U_{rf} \quad (3-5)$$

Their total harmonic distortion factors (THD) are defined as follows:

$$THD_V = \frac{100}{U_{of}} \sqrt{\sum_{k=1}^{\infty} U_{ok}^2 [\%]} \quad (3-6)$$

Where U_{ok} is the magnitude of the harmonic elements of the capacitor output voltage.

In this paper, the base frequency f_1 is 50Hz, the lowest frequency of harmonic f_{k1} is 5kHz, and the cut-off frequency f_c is set as 500Hz.

Since $f_1 \ll f_c$, $\omega_1 L \ll \frac{1}{\omega_1 C}$. So $\omega_1 L$ has a tiny resistance on base wave signal, and $1/\omega_1 C$ has a

minimum split from base wave signal. Meanwhile, since $f_c \ll f_{k1}$, $\omega_{k1} L \gg \frac{1}{\omega_{k1} C}$. So $\omega_{k1} L$ has a large resistance on base wave signal, and $1/\omega_{k1} C$ has a large split from base wave signal. So the filter blocks the lowest frequency of harmonic signal. And for the other harmonic signals which have higher frequency, the filter will block them too.

The system parameters L and C are designed within the THD value required in the system. The inductor and capacitor value can be obtained as:

$$L = \frac{100\sqrt{2}R_o \cdot TH_2}{D \cdot THD_1} \quad (3-7)$$

$$C = \frac{THD_1 \cdot TH_1}{THD_V \cdot R_o \cdot TH_2} \quad (3-8)$$

Since the inductor is chosen as 1mH already, the capacitor could be calculated as:

$$C = \frac{TH_1 \cdot D}{L \cdot 100\sqrt{2} \cdot THD_V} \quad (3-9)$$

Where D is duty ratio, $TH_1 = \frac{1}{\omega_s^2 \pi} \sqrt{\sum_{k=1}^{\infty} \frac{\sin^2 kD\pi}{k^6}}$

Considering other condition, such as the overheat of capacitor, the value of C couldn't be too large. Otherwise the impedance will be too small, since it depends on $1/\omega C$.

So the value to define for the capacitance is 0.22μF in the circuit.

3. Circuit Design

When it comes to the design of the unit, the value will be adjusted a bit to ensure the effect of filter. And the filter circuit finally is designed as in figure 3-4.

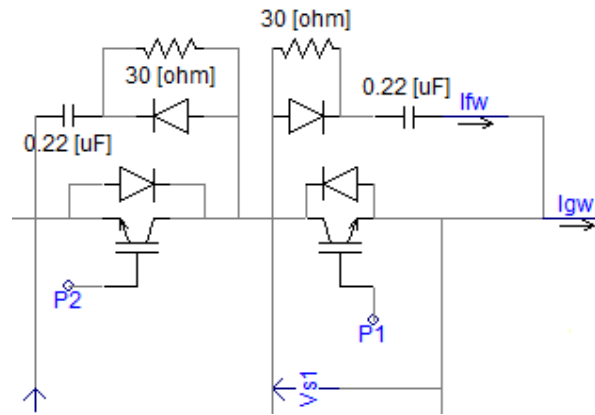


Figure 3-4 Filter circuit

And for the circuit of the inverter, the value to chose is similarly. The circuit of inverter unit is given in figure 3-5.

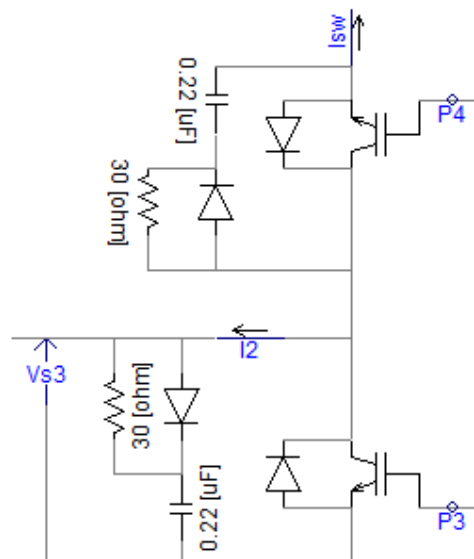


Figure 3-5 Inverter unit

3. Circuit Design

As mentioned in previous sections, the principle of the work and the voltage test method are already confirmed. And based on them, the design of actuating signal control circuit is shown in figure 3-6.

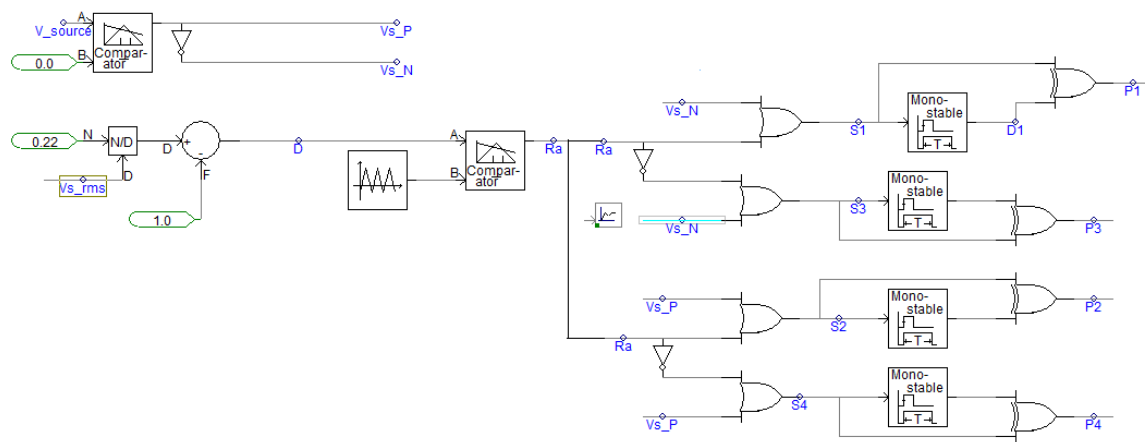


Figure 3-6 Actuating signal control

4. Experiment and Simulation

4.1 General simulation result

Supposing the system voltage is fluctuated from 150V to 200V, run the simulation model for AC chopper compensator with PSCAD simulation software. The simulation results indicate that when line the voltage drops down from 200V to 150V and then rises to 200V, the load voltage RMS value keeps around 220V stable. Voltage waveforms of u_{sys} , u_{com} , u_{load} are presented in Figure 4-2, 4-3, and 4-4 respectively. In conclusion, the simulation results prove the accuracy of the compensation method.

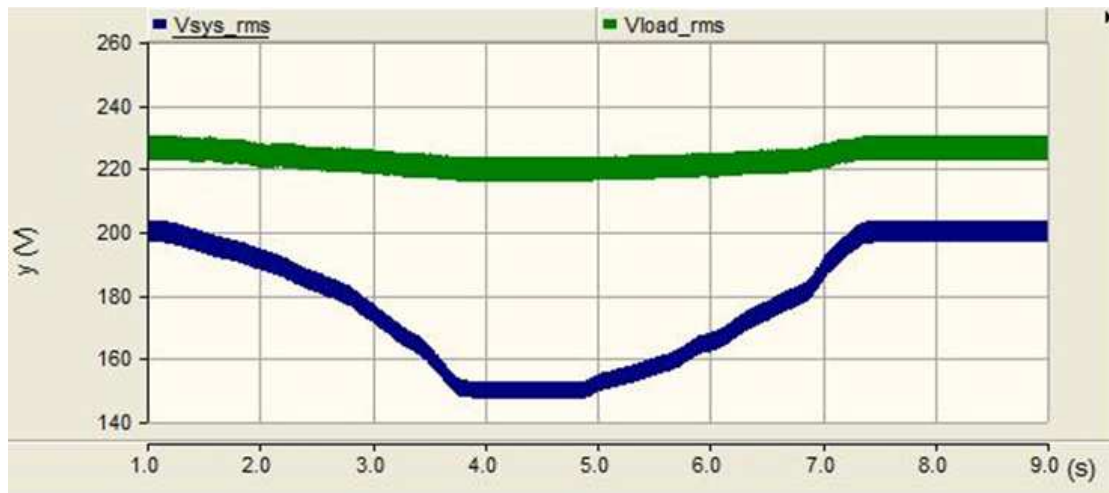


Figure 4-1 RMS value of voltage waveform

Green line: Voltage on load side/Blue line: System voltage

4. Experiment and Simulation

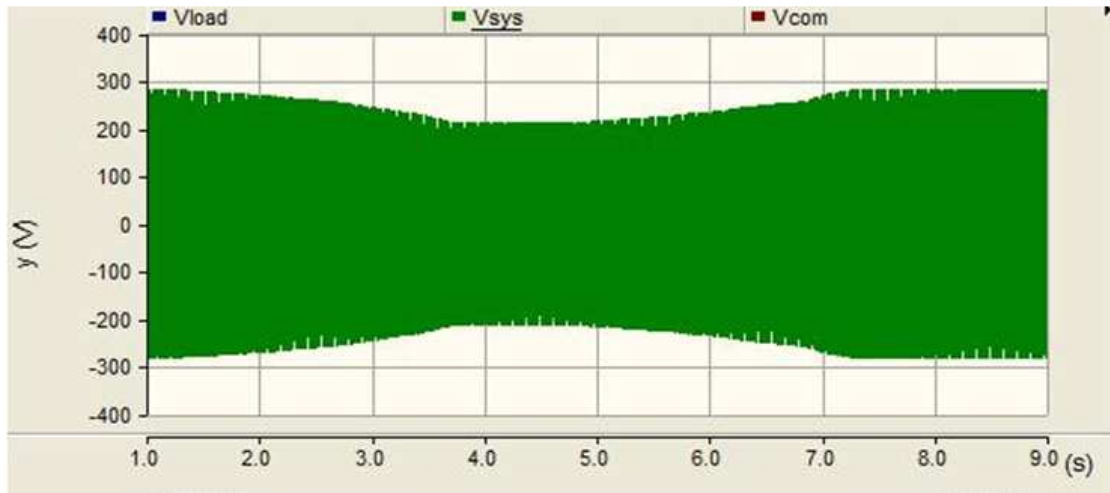


Figure 4-2 Zoom-in graph of system voltage u_{sys}

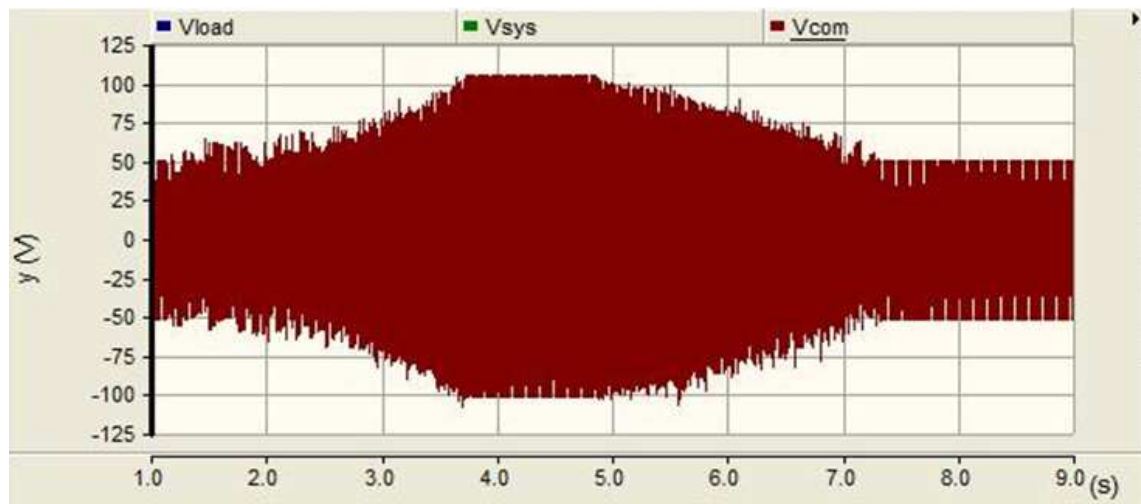


Figure 4-3 Compensation output voltage waveform

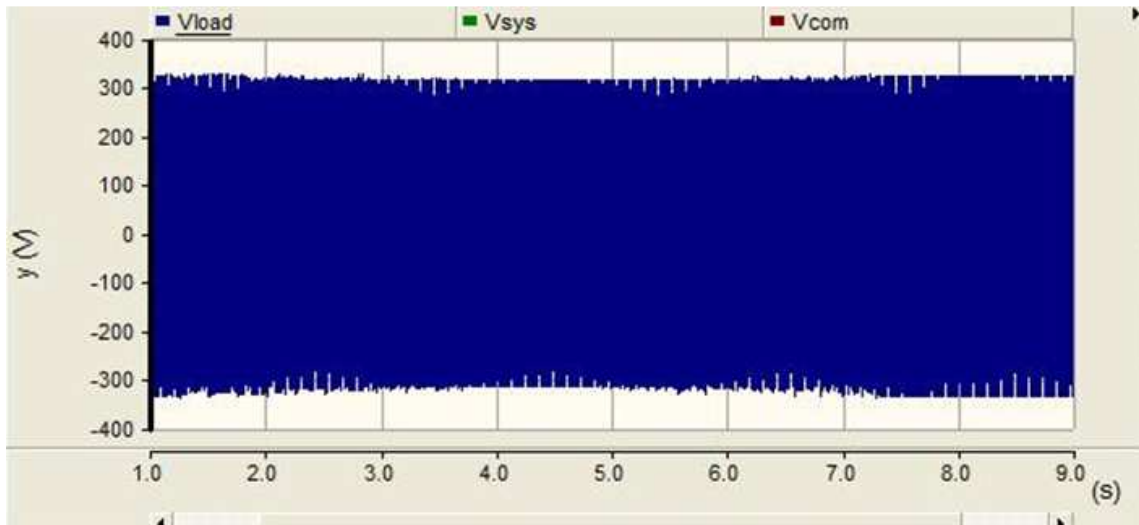


Figure 4-4 Load voltage waveform

The proposed circuit is implemented and tested with a 500W load. Figure 4-1 shows the variation of the system voltage and load voltage. The voltages are measured by a Fluke 434 Three Phase Power Quality Analyzer. From the experiment results, it can be seen that when system voltage drops down to 140V gradually, the load voltage is 220V and it doesn't change. When system voltage rises above 200V, the circuit stops and the bypass switch closes, load voltage changes according to system voltage. After system voltage drops to 200V again, the circuit runs again. The experimental results agree with the simulation results.

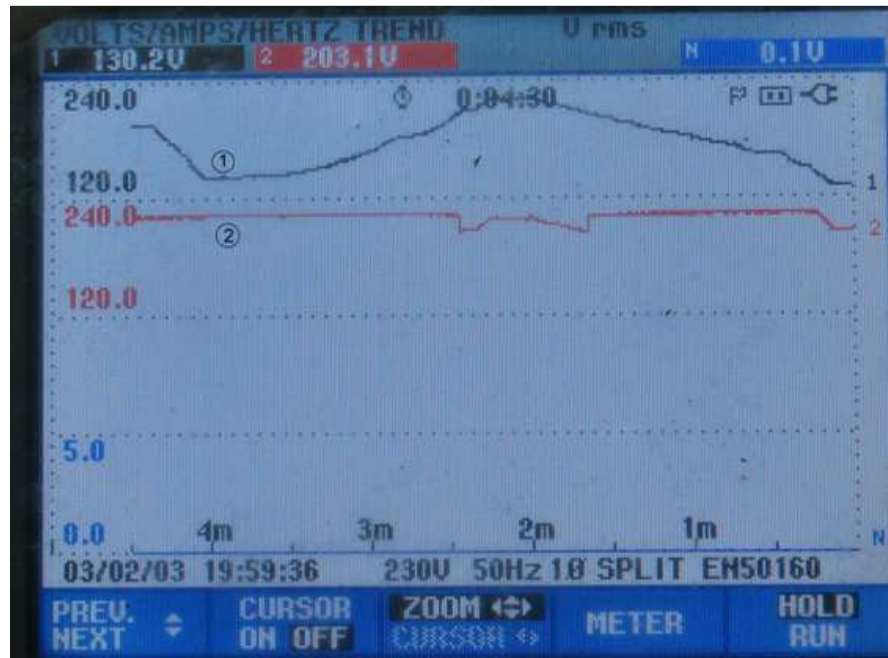


Figure 4-5 RMS value of voltage waveform

4.2 Adjustment and advanced experiment

In this section, some adjustments on the circuit will be operated, and the influence could be recognized by the simulation results. Actually, two experiments will be given in the next work.

The experiment to detect the influence of non-complementary control strategy is given first.

Experiment purpose: reduce the carrier wave frequency, detect whether the input voltage will fall off when S1 turn on.

Program: LM_1126_01, duty cycle: 0.3, frequency: 500Hz

Measuring point:

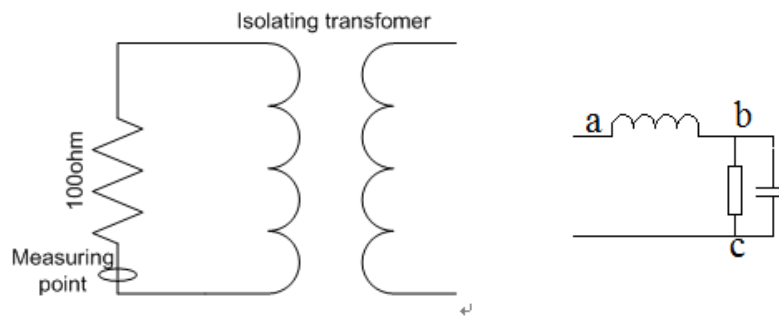


Figure 4-6 Measuring point

A 100 ohm resistance is parallel with the primary winding of the isolating transformer which is shown in figure 4-6. The current through the resistance is measured and the such measuring wave is considered as the reference value for the isolating transformer primary winding. And the positive half wave in CH2 is assumed as the output from the primary winding of the isolating transformer.

Firstly, consider the case when the AC chopper does not operate, which means in positive half wave, S1, S2 and S4 turn on, S3 turns off continued; in negative half wave, S1, S3, and S2 turn on, S4 turn off continued. The output voltage is corresponding to the input voltage, without fall off and loss. Observe the waveform.

The parameters are shown in table 4-1.

Input voltage(V_{ac})	Inductance(mH)	Conductance(μF)	Resistance(Ω)	Buffering circuit
15	2	100	1k	Without S3, S4 buffer

Table 4-1 Parameters

4. Experiment and Simulation

Simulation result:

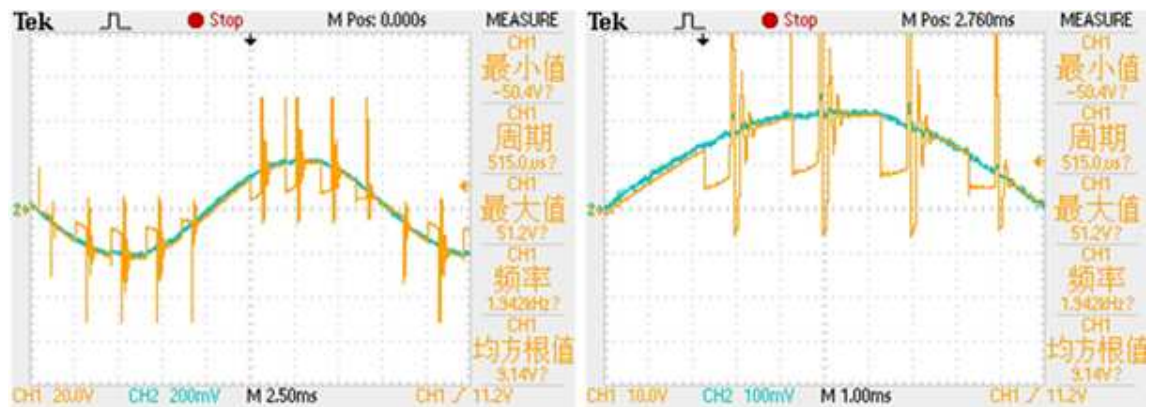


Figure 4-7 comparison of voltage on different winding in normal size and in expanding view

CH1: voltage on secondary winding of isolating transformer

CH2: voltage on primary winding of isolating transformer

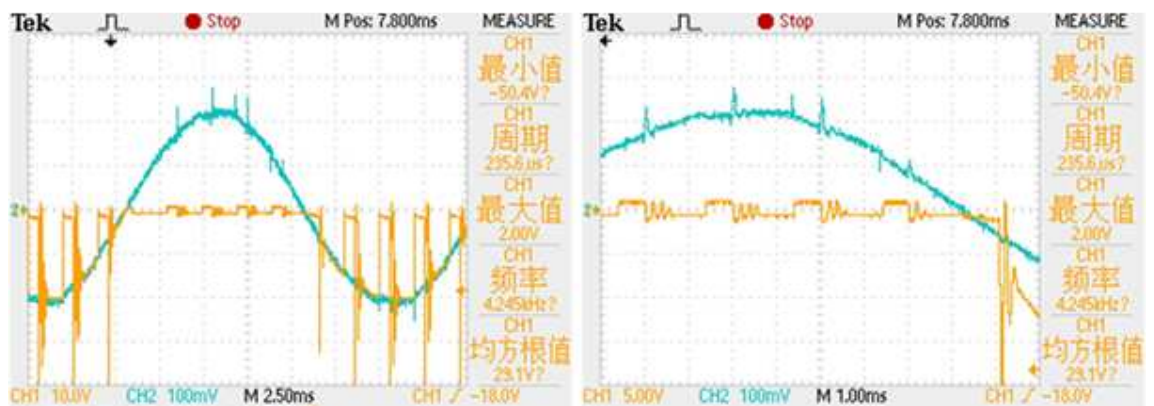


Figure 4-8 comparison of voltage on S2 and primary winding in normal size and in expanding view

CH1: VEC on S2 in positive half wave

CH2: voltage on primary winding of isolating transformer

4. Experiment and Simulation

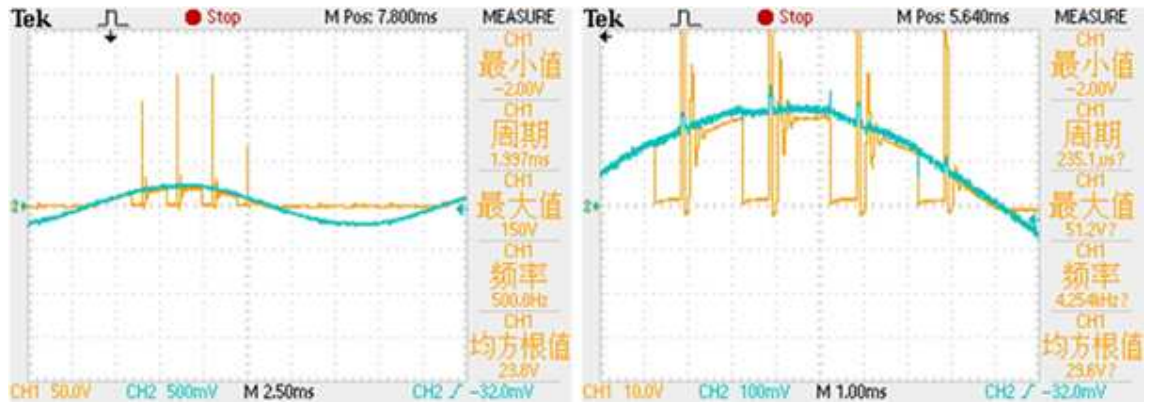


Figure 4-9 comparison of voltage on S1 and primary winding in normal size and in expanding view

CH1: VEC on S1 in positive half wave

CH2: voltage on primary winding of isolating transformer

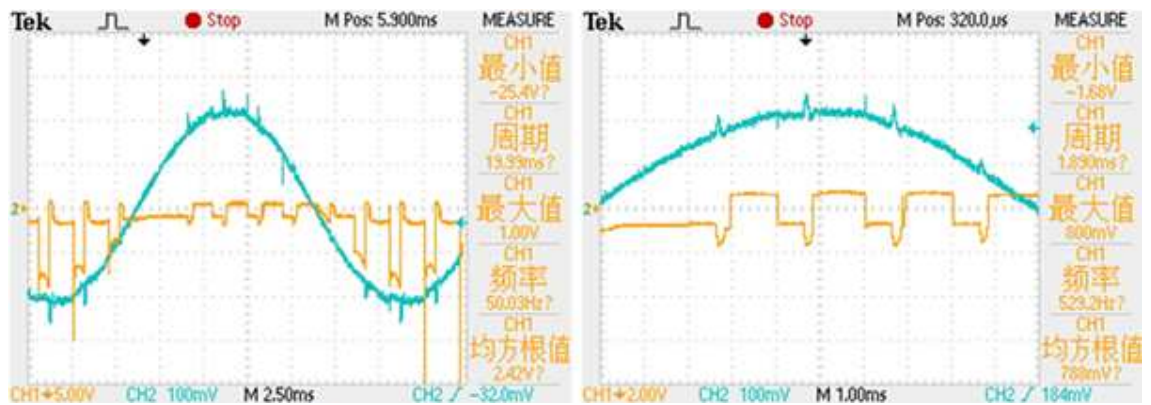


Figure 4-10 comparison of voltage on S4 and primary winding in normal size and in expanding view

CH1: VEC on S4 in positive half wave

CH2: voltage on primary winding of isolating transformer

4. Experiment and Simulation

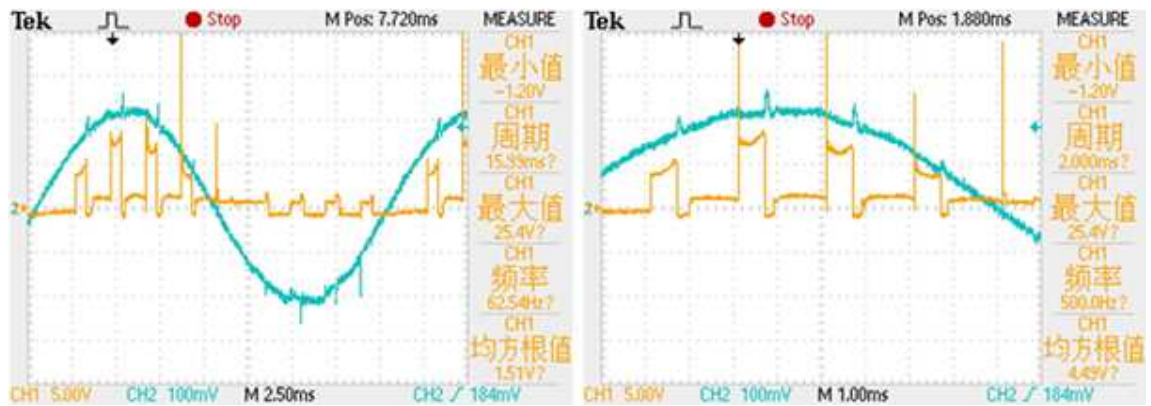


Figure 4-11 comparison of voltage on S3 and primary winding in normal size and in expanding view

CH1: VEC on S3 in positive half wave

CH2: voltage on primary winding of isolating transformer



Figure 4-12 comparison of voltage on resistance and primary winding

CH1: voltage on the resistance

CH2: voltage on primary winding of isolating transformer

4. Experiment and Simulation

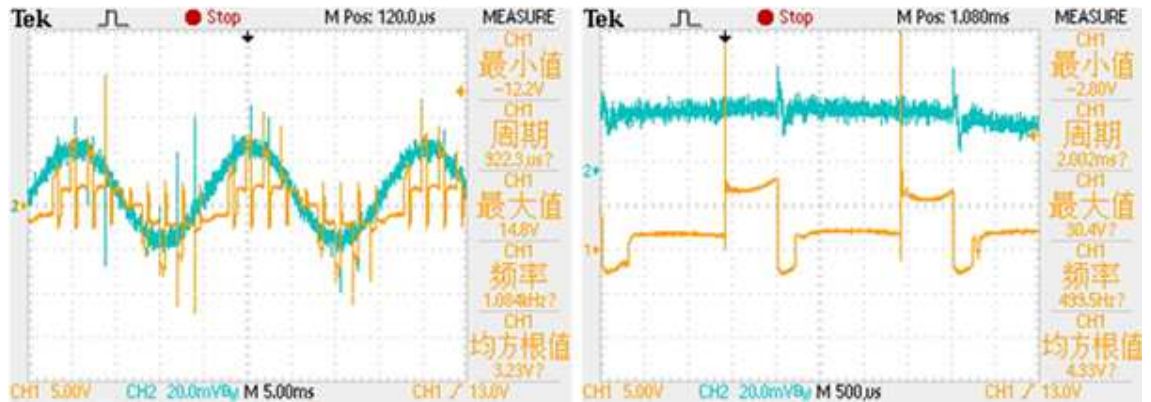


Figure 4-13 comparison of input voltage and voltage on primary winding in normal size and in expanding view

CH1: input voltage Vac

CH2: voltage on primary winding of isolating transformer

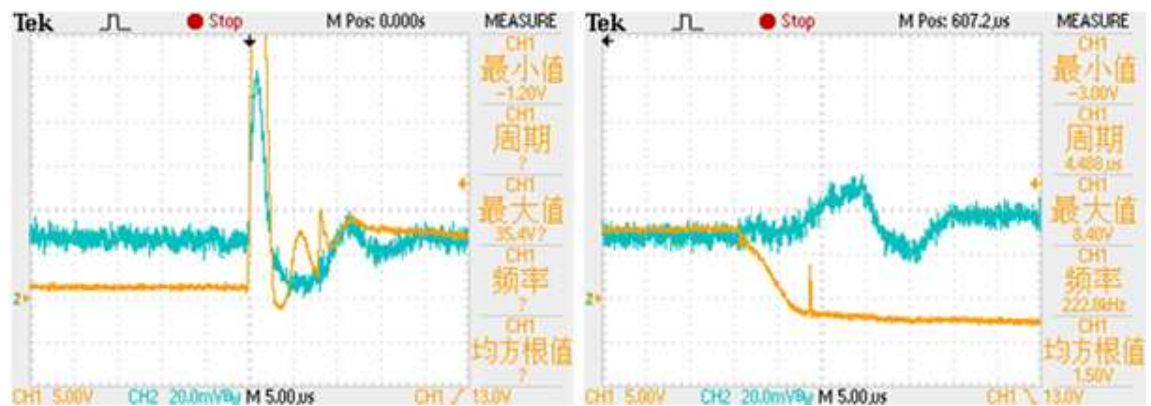


Figure 4-14 comparison of the peak value of input voltage and voltage in primary winding

CH1: peak value in figure 4-13

CH2: voltage on primary winding of isolating transformer

In figure 4-14, the dead zone of the expanding of peak is shown in the left one. And the dead zone when S1 turns off is shown in the right one.

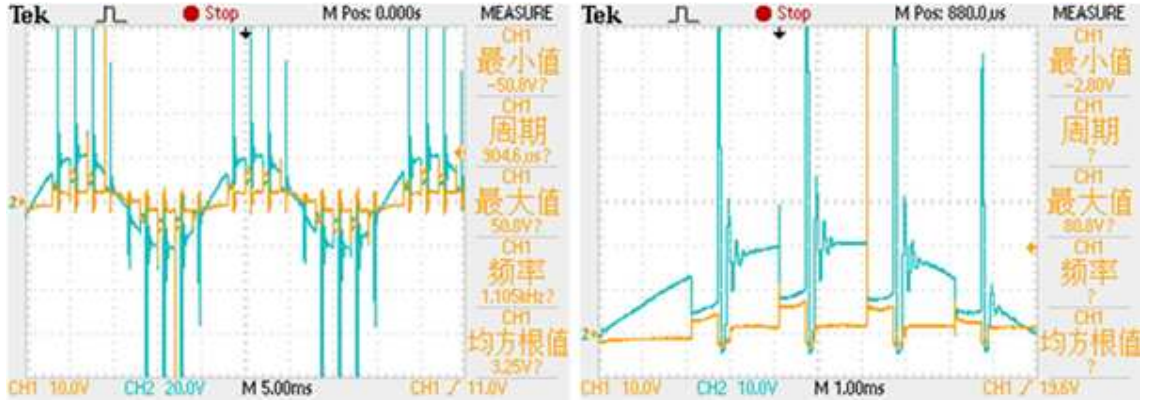


Figure 4-15

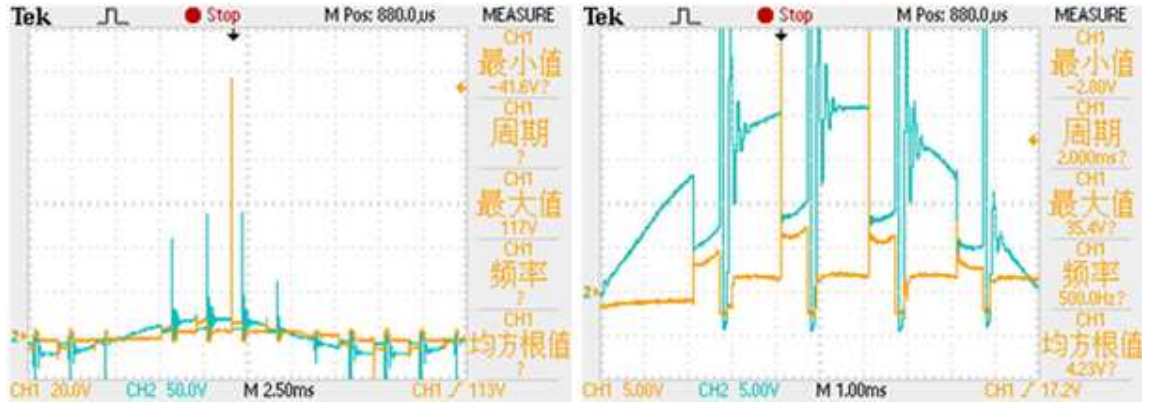


Figure 4-16

In figure 4-16, the peak of V_{ac} is extreme high which is shown in the left one. And there is a partial voltage seen from the wave in the right one when S1 turns on. The causation is that the impedance of isolating transformer is too large, but the load impedance is not large enough.

When the voltage in primary winding is 11.5V, the voltage on the resistance is 7.5V. So the partial voltage on the isolating transformer impedance is 4V. The leakage inductance is calculated in equation 4-1:

$$L = \frac{4}{2\pi * 50} = 0.0127(H) \quad (4-1)$$

4. Experiment and Simulation

The parameters are modified and are shown in table 4-2

Input voltage(V_{ac})	Inductance(mH)	Conductance(μF)	Resistance(Ω)	Buffering circuit
15	2	100 50 20	1k	Without S3, S4 buffer

Table 4-2 Parameters

The conductance is reduced, and load resistance is increased in order to increase the partial voltage on load and reduce the partial voltage on isolating transformer impedance.



Figure 4-17 comparison of input voltage V_{ac} and output voltage in normal size and expanding view

CH1: input voltage V_{ac}

CH2: output voltage from isolating transformer

The parameters are modified and are shown in table 4-3

Input voltage(V_{ac})	Inductance(mH)	Conductance(μF)	Resistance(Ω)	Buffering circuit
15	2	100 50 20	1k	No

Table 4-3 Parameters

4. Experiment and Simulation

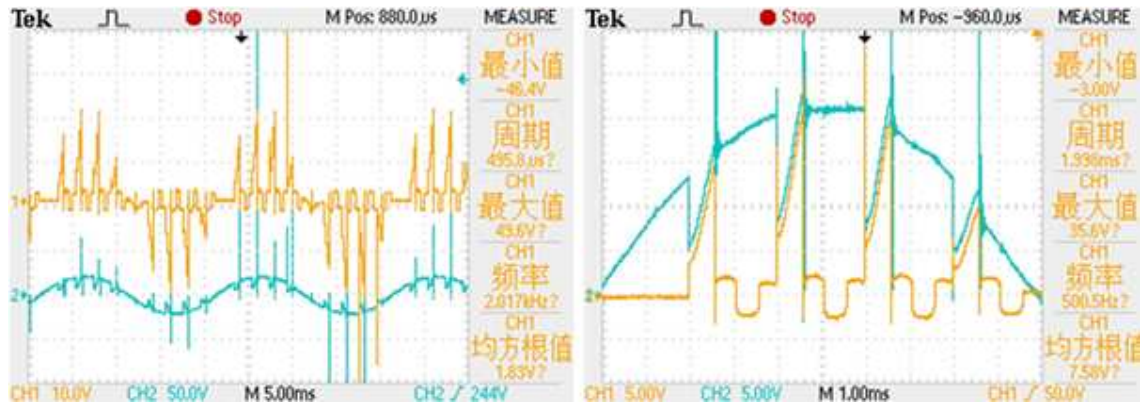


Figure 4-18 comparison of input voltage Vac and output voltage in normal size and expanding view

CH1: input voltage Vac

CH2: output voltage from isolating transformer

Seen from the right one of figure 4-18, the first peak is higher when the buffer circuit is removed, and the oscillation is reduced.

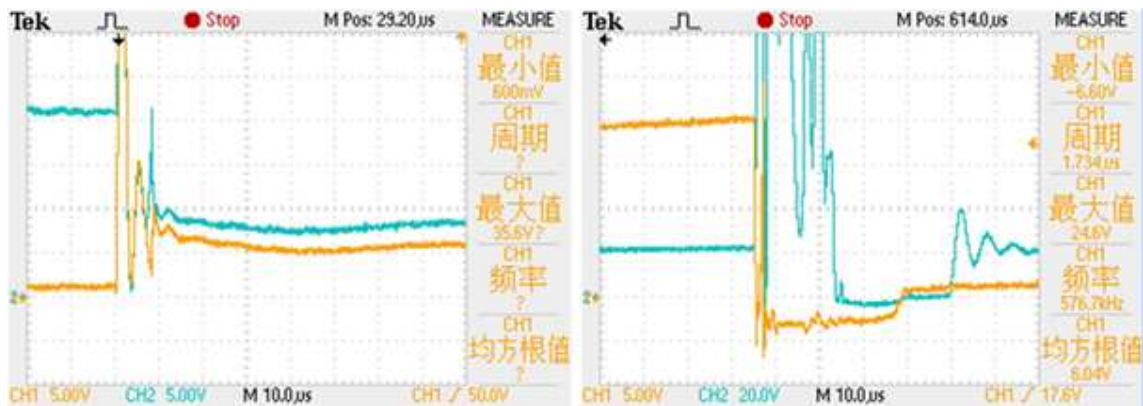


Figure 4-19 Waveform when S3 or S1 turns off

The left one of figure 4-19 is the wave when S3 turns off. The oscillation of peak is about 10μs, which is the dead zone.

The right one of figure 4-19 is the wave when S1 turns off. And the oscillation is totally disordered.

On the whole, while there isn't any conductance for compensating reactive power, the output voltage of isolating transformer will fall off obviously when IGBT acts. And when the conductance is added, the sag is compensated.

4. Experiment and Simulation

The experiment of duty cycle adjustment with load carried in given below.

Experiment purpose: Synchronization and loaded experiment, including AD sampling and duty cycle adjustment.

Program: LV_1210_01, frequency 5kHz

Connecting way: input 380V, output 220V

Parameters are shown in table 4-4, when $V_{in}=173V$, $V_{load}=221V$

Parallel Conductance(μF)	Inductance(mH)	Conductance(μF)	Load(W)	Buffering circuit
25 (50 slots)	2	50	500	$C=0.22\mu F$, $R=30\Omega$

Table 4-4 Parameters



Figure 4-20 Source voltage and its expanding graph

Seen from the figure 4-20, there are glitch at the peak.

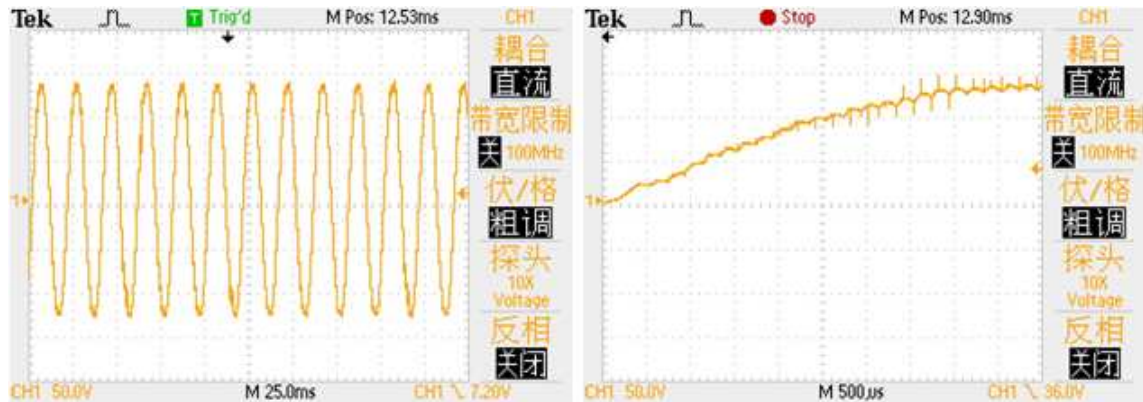


Figure 4-21 Input voltage and its expanding graph

Seen from the figure 4-21, the input voltage is not smooth enough.

4. Experiment and Simulation

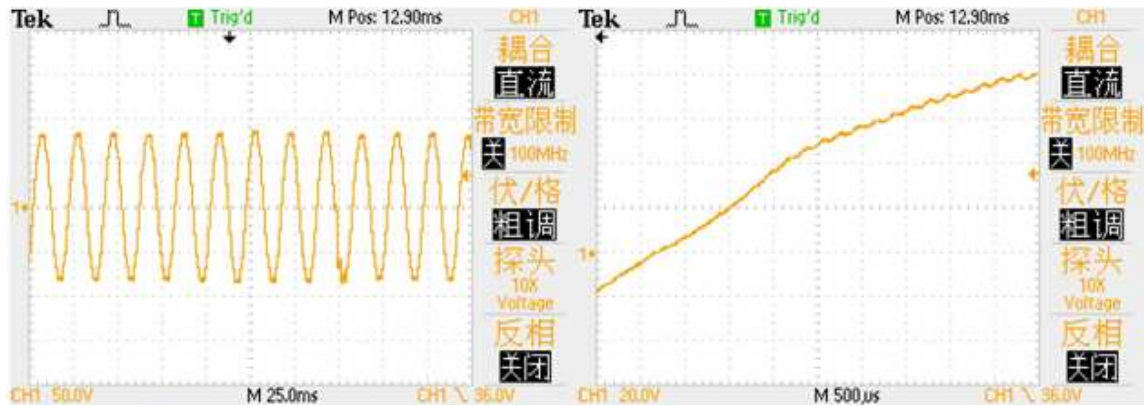


Figure 4-22 Compensation voltage and its expanding graph

Seen from the figure 4-22, the peak is absorbed by the filter since there are filter inductance and capacitance in the filter circuit. According to the parameters that $L=2\text{mH}$ and $C=50\mu\text{F}$, the harmonic frequency on 4.9kHz is attenuating to 1%. But when it comes to the expanding graph, the wave is not smooth enough and there is still some harmonics.

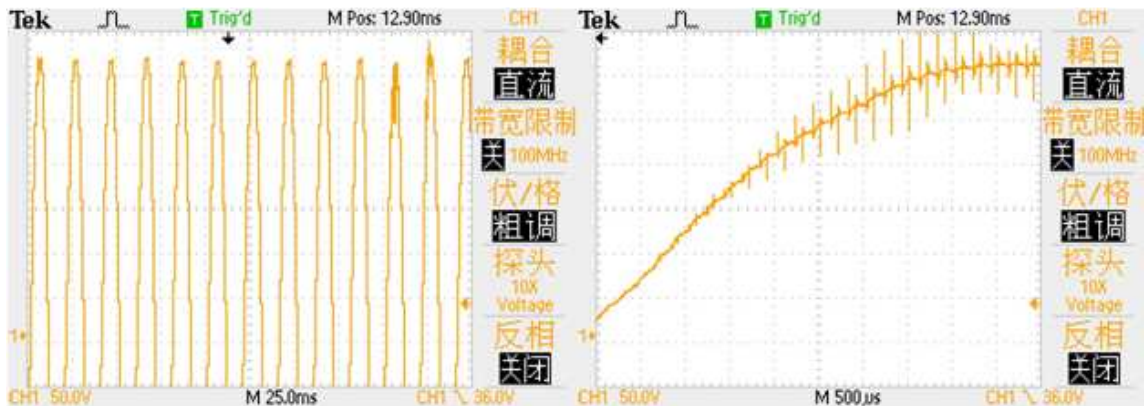


Figure 4-23 Load voltage and its expanding graph

Seen from the figure 4-23, there are disturbance on the peak of load voltage due to the influence of the input voltage from the isolating transformer.

From the above, the disturbance on peak voltage is found to be not able to filtrate by filter. It's because the peak value is in front of the AC-chopper circuit, and it could not be influence by the filter.

And more experiments are performance to detect the influence of the actuating signal.

4. Experiment and Simulation



Figure 4-24 General view and zoom-in view of waveform when S1 turns off

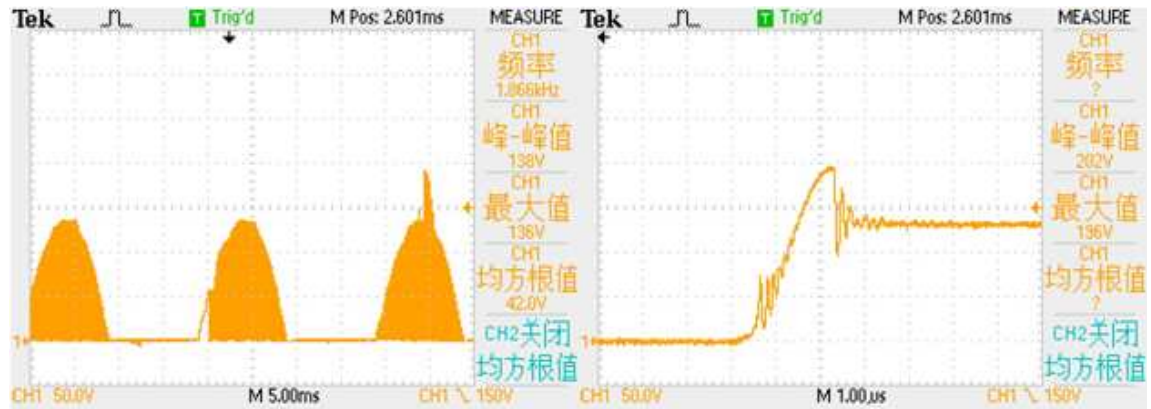


Figure 4-25 General view and zoom-in view of waveform when S2 turns off



Figure 4-26 General view and zoom-in view of waveform when S3 turns off



Figure 4-27 General view and zoom-in view of waveform when S4 turns off

Seen from four figures shown above, there is too much oscillation when S2, S3 and S4 turn off.

4.3 Conclusion

This thesis proposed a voltage compensator based on an AC buck chopper, which is operated using the strategy of non-complementary control without current detection. It is suitable for compensation long-term voltage sags and could adjust pulse widths according to the ratio of required output in real time. Simulations and experiment results proved functionality of this circuit. The only drawback of the circuit is that PWM pulsations will produce harmonic current. We will settle this problem in the next work additionally.

4.4 Harmonic analysis

System voltage is defined as follow:

$$u_{sys} = U_m \sin(2\pi f_0 t) \quad (4-2)$$

where U_m and f_0 are the magnitude and frequency of the system voltage. The output u_{com} is expressed as follow:

$$u_{com} = S(t) \times u_{sys} \quad (4-3)$$

where $S(t)$ is switching function expressed as:

$$S(t) = \begin{cases} 1 & nT_s \leq t \leq nT_s + DT_s \\ 0 & nT_s + DT_s \leq t \leq (n+1)T_s \end{cases} \quad n = 0, \pm 1, \pm 2 \dots \quad (4-4)$$

where T_s is switching period. The Fourier series of u_{com} by substitution of (4-2) and (4-3) into (4-5) is obtained:

$$u_{com} = DU_m \sin(2\pi f_0 t) + \frac{U_m}{\pi} \sum_{m=1}^{\infty} \frac{\sin \alpha}{m} \{ \sin[2\pi(mf_s + f_0)t - \alpha] - \sin[2\pi(mf_s - f_0)t - \alpha] \} \quad (4-5)$$

where f_s is frequency of PWM, and $\alpha = m\pi D$. It is indicated that there were harmonic in u_{com} , the frequency of harmonic distributes at $mf_s \pm f_0$. Reducing harmonic voltage improving switching frequency and varying L and C2 are useful for reducing harmonic voltage.

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