A HYBRID SWITCH BASED ARCLESS VOLTAGE REGULATOR

by

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ABSTRACT

XIWEN XU. A hybrid switch based arcless voltage regulator. (Under the direction of DR. TIEFU ZHAO)

The voltage regulator is a mechanism that permits the change in turns ratio or output voltage of a distribution transformer for providing a constant magnitude voltage to the load. The arc occurs under oil in each tap changing operation because one of the moving contactors needs to move from one tap to another. The arcing results in an ablation of contact material every time a tap change is made, which reduces the lifetime of the transformer. Due to the increasing requirement of more frequent tap changing operations, the power electronics assisted method becomes an attractive solution to eliminate the arcing during tap changing.

This thesis first reviews the development of arcless technology applied to the voltage regulator. Then, a hybrid switch based arcless voltage regulator is presented to eliminate the arc in tap changing events by using two anti-parallel thyristors and two electro-mechanical contactors. Simulation results validate the feasibility of the proposed arcless voltage regulator. A 12 kVA arcless voltage regulator prototype is developed to validate the arcless procedure. This proposed method requires minimum changes to the existing step-type voltage regulator and increases the number of operations and the lifetime of the conventional voltage regulator.

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LIST OF ABBREVIATIONS

A	Ampere
AC	Alternating Current
ADC	Analog to Digital Converter
AVR	Arcless Voltage Regulator
CT	Current Transformer
DC	Direct Current
DSP	Digital Signal Processor
F	Farad
GPIO	General Purpose Input/Output
GTO	Gate Turn-Off (thyristor)
HVDC	High Voltage Direct Current
I/O	Input/Output
IGBT	Insulated Gate Bipolar Transistor
J	Joule
LDO	Low Drop Output
LED	Light-Emitting Diode
MCU	Microcontroller
mH	Millihenry
ms	Millisecond
PA	Preventive Autotransformer
PCB	Printed Circuit Board

s	Second
SCR	Silicon Controlled Rectifier
SiC	Silicon Carbide
T	Tesla
V	Volt
VR	Voltage Regulator
W	Watt
Ω	Ohm

CHAPTER 1: INTRODUCTION

1.1 Introduction

Requirements for electrical power become more challenging every day in terms of both quality and quantity. “Quality” means that consumers need a stable voltage without distortions and interruptions. “Quantity” means that the user can draw as much load as needed without reducing the quality of the supply [1]. These requirements come from industry as well as from domestic consumers, and each requirement influences the other.

Figure 1-1 Single-phase step-voltage regulator [1]

Maintaining voltage magnitude within a specified range is an important component of power quality. Power transformers and feeders impose their own impedance, and the amount of voltage drop depends on the loads and, consequently, the currents that flow through them. Voltage magnitudes decrease along the feeder, which means that consumers at the end of the feeder will have the lowest voltage.

Distribution systems must have the ability to maintain the voltage magnitudes in a specific range to meet the requirements from domestic customer. This is accomplished through the use of voltage-control equipment and effective system design. Regulating power transformers (load-tap-changing transformers, or LTCs), three-phase step-voltage regulators, single-phase step-voltage regulators, and Auto-Boosters® are typical transformer-type equipment used to improve the voltage "profile" of a power system [1].

The single-phase step-voltage regulator, shown in Figure 1-1, that is used in substations and on distribution system feeders and laterals. Figure 1-2 shows the locations on a power system where voltage regulators are commonly applied.

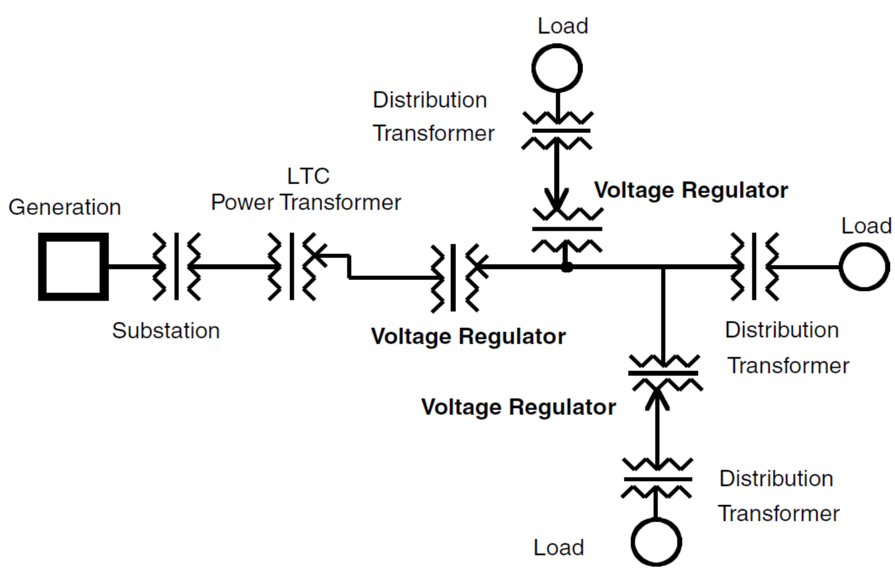


Figure 1-2 Power system [1]

1.2 Voltage Regulator

Electromechanical Voltage Regulator, also known as Tap Changer, is a mechanism that permits the change in turns ratio or output voltage of a distribution transformer for providing a constant magnitude voltage to the load. Transformer tap is a connection which is taken out from a node located between two ends of a winding. This permits changes in voltage or turns ratio of the transformer after it has left the factory. The reasons to have a series of the tap in the transformer are as follows:

a. To fix the secondary voltage against the primary voltage changes;
b. To change the secondary voltage;
c. To provide an auxiliary secondary voltage for a specific application such as lighting;
d. To provide a natural point for earthing or conducting unbalanced current in three-wire single-phase circuits or four-wire three phase circuits [2].

The typical step-type voltage regulator provides ±10-percent regulation in 32 steps of approximately 5/8 percent each, which is depicted in Figure 1-3. A step-voltage regulator is a tapped autotransformer. In a voltage regulator, the winding in the high-voltage side at a two-winding transformer would be referred to as the shunt winding, while the winding in the low-voltage side would be referred to as the series winding. The series winding is connected to the shunt winding in order to boost or buck the applied or primary voltage. Nine stationary contacts are connected with nine nodes that divided the series winding into eight equaled sections. The bridging reactor commonly referred to as a preventive autotransformer (PA). Eight tapped sections of the series winding, each

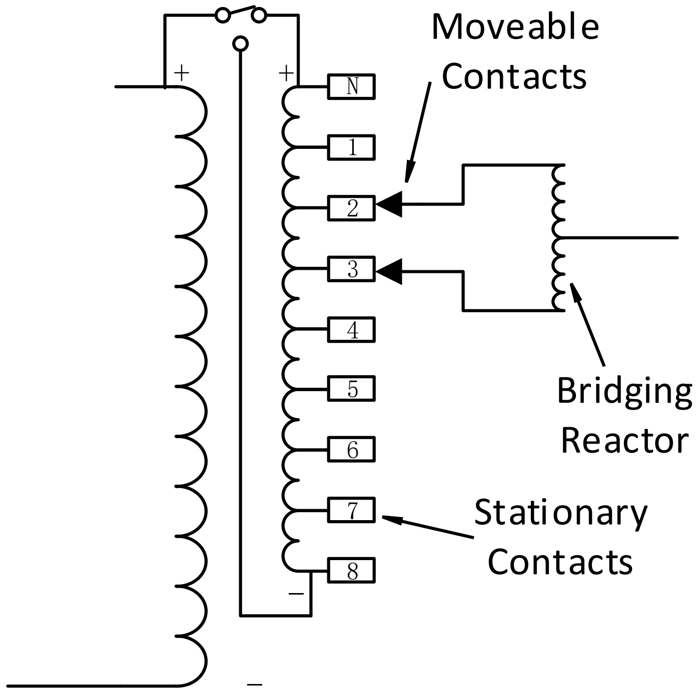


Figure 1-3 Conventional step voltage regulator

representing essentially 5/4 percent of the input voltage, are brought out to a specially designed dial switch in Figure 1-4 to facilitate the changing of these tap connections to the series winding, thus changing the output voltage of the regulator. Two moving contacts are used with the PA to avoid a momentary loss of power during the transition from one tap connection to the next.

The process of moving from one voltage regulator tap to the adjacent voltage regulator tap consists of closing the circuit at one tap before opening the circuit at the other tap. The movable tap-changer contacts have two branches. They move only one of the movable contacts at one time. There are two types of position for the movable contacts. The movable tap-changer contacts are both on the same stationary tap would be referred to as a nonbridging (symmetrical) position, while the movable contacts on two adjacent taps would be referred to as a bridging (asymmetrical) position. The movable contacts move

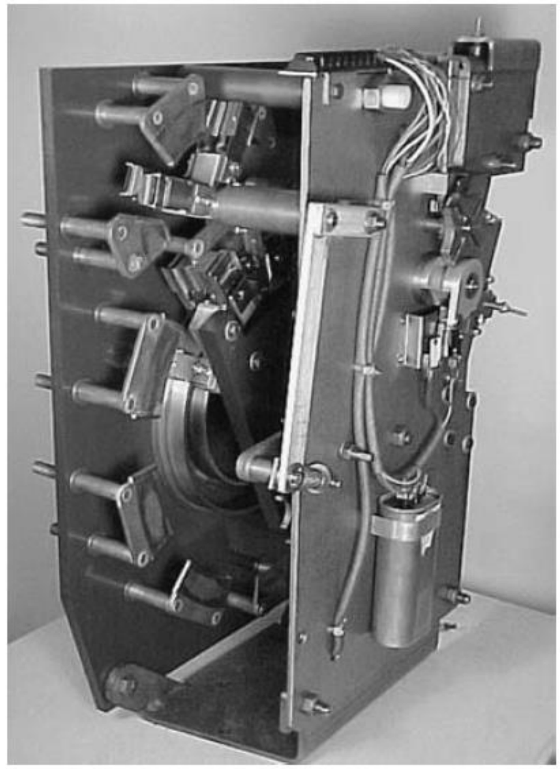
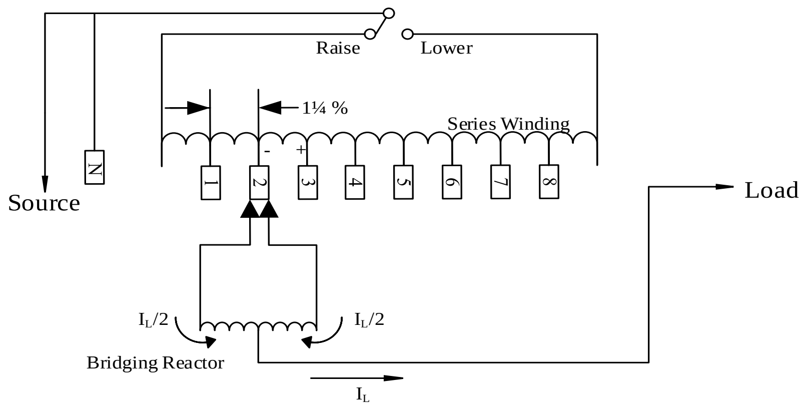


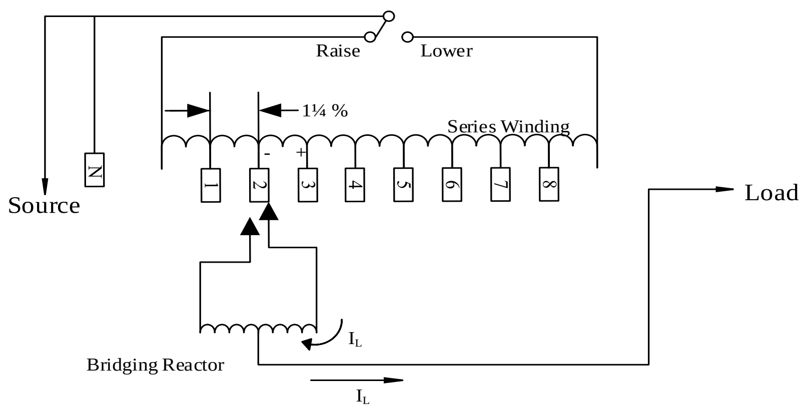
Figure 1-4 Dial switch [1]

through stationary taps alternating in eight bridging and eight nonbridging (symmetrical) positions. Figure 1-5(a) shows the two-movable tap-changer contacts on a symmetrical position. In this position, each of path shares half of the load current.

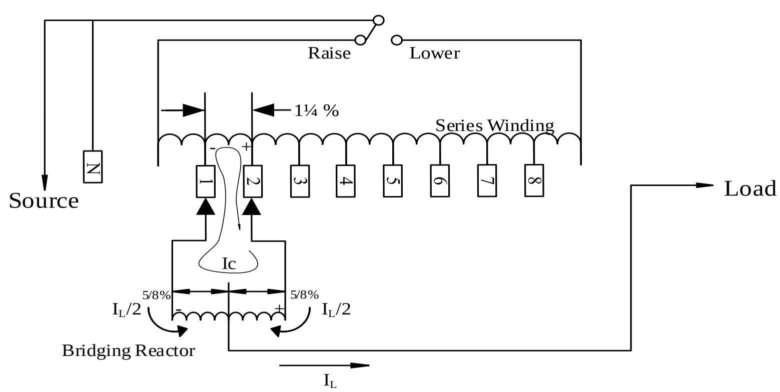
Tap changer moving event is happening as shown in Figure 1-5(b). One of the contacts starts moving from tap #2 to tap #1. The arc occurs while the contact starts to leave from the tap #2 and transfers the current from the left path to the right path before it moves to the adjacent tap #1. The load current is maintained since one of the moving contacts remains on a stationary contact (tap #2). At this juncture, all the load current flows through one-half of the reactor, magnetizing the reactor, and the reactance voltage is introduced into the circuit for about 33 ms during the tap change.



(a) Two movable contacts on the same stationary contact (symmetrical position)



(b) One movable contact on stationary contact (asymmetrical position)



(c) Two movable contacts on adjacent stationary contacts (bridging position)

Figure 1-5 Conventional tap changer switching sequences

Figure 1-5(c) shows the movable contacts in a bridging position; voltage change is one-half the 5/4% tap voltage of the series winding because of its equivalent center tap located in the middle of two adjacent taps (tap #1 and tap #2).

1.3 Problems of Conventional Voltage Regulator

The switching sequences of a conventional voltage regulator are introduced in the previous section. The interruption of the high current in the mid-voltage transformer can lead to an arc between contacts. The arc occurs under oil and extinguishes as the moving contact travels to the next stationary contact. Although there are several designed alternatives to reduce the degree of arc, it will still occur during each tap change [3]. An arc existing in the tap changing event can cause a lot of consequential deleterious effects. For example, an ablation of contact material in each tap changing event can cause contact burn and oil contamination, which leads to early failure or needs frequent maintenance. It will reduce the reliability and the lifetime of voltage regulators. One of the solutions to reducing the effect of contact wear is replacing the material of stationary contacts and movable contacts to an arc-resistant material. But the conductivity of this arc-resistant material is not as good as a copper material which also limits the rating of the tap changer.

With the increasing penetration of the renewable energies, the voltage regulators are operated more frequently than before. The tap changing operation requires to quickly disconnect from one stationary contact and quickly reconnect to the next according to the arcing nature. This is accomplished by adding some springs in the mechanism to minimize the length of arcing time in the past years. But it cannot meet the requirements of renewable energy systems in terms of the switching speed.

Besides, the arcing during each tap change under oil also generates a combustible gas. Although the Simens-Allis employs a unidirectional breather which continuously vents this gas, the exposure to air, plus the arcing in the oil, accelerates the degradation of the oil requiring voltage regulator oil to be filtered more often than would be necessary if the arcing could be eliminated [3].

1.4 Advantage of Arcless Voltage Regulator

There are several distinct advantages of arcless voltage regulators. The lifetime of a voltage regulator can be increased by eliminating the arcing. There is no contact wear any more if the arcing does not exist in tap changing events, which can decrease the failure of tap changers and the contact burning problem. It will increase the reliability as well as the lifetime of voltage regulators. Table 1-1 shows the maintenance cost of a conventional voltage regulator in 1984. There is no ablation in the contact materials and contactors will not need to be replaced because of the arcless tap changing operations. The arcless approach can also decrease the maintenance frequency significantly, in other words, decrease the cost of maintenance.

Table 1-1 Maintenance cost for conventional voltage regulator [3]

Cost to remove regulator from service	$ 120.00
8 Main Stationary Contacts	$ 334.16
2 Main Moving Contacts	76.20
1 Neutral Contact	58.11
2 Reversing Switching Stat. Contacts	89.06
2 Reversing Switch Moving Contacts	73.56
Freight on Parts	28.40
Total Cost of Parts	$ 659.49
Labor to untank, change out contacts, and retank	155.00
Cost to recondition oil	125.00
Cost to place back in service	120.00
Total Savings	$ 1,179.49

All of these advantages, in other words, will potentially increase the numbers of electrical operation of the conventional voltage regulator.

1.5 Literature Review

There are a lot of arcless voltage regulator topologies proposing in the past years to eliminate the arc. A literature review [4-20] is conducted specifically in power electronics assisted arcless tap changers, including patents from Allis-Chalmers/Siemens, Maschinenfabrik Reinhausen, General Electric, Elin-Union, National Grid, Areva T&D, Pennsylvania Transformer Technology, Imperial Innovations, and Alstom Grid.

The previous power electronic assisted arcless tap changer solutions are classified into different categories based on the main technical novelties. The arcless solution categories include Vacuum Interrupter (VI) based, auxiliary winding (1/2 tap), diverter design for tap changing transformer, SCR thyristor and IGBT as an add-on accessory.

An early design of arcless voltage regulator is introduced Vacuum Interrupter (VI) switches into the conventional voltage regulator. this approach is still used today to eliminate the arcing. Vacuum Switch technologies usually require the use of bridging reactors. The bridging reactor is itself a transformer, of perhaps one-quarter of the size of the main transformer. It significantly adds to the cost and weight of the total assembly. It typically will also add to total internal losses, the resulting heat having to be dissipated with additional tank cooling provisions. [5]

The patent [6] proposed a solid-state thyristor voltage regulator in Figure 1-6. The operation speed of this solid-state topology is faster than the operation speed of conventional voltage regulators. But this topology has reliability issue because all the thyristor must be continuously active.

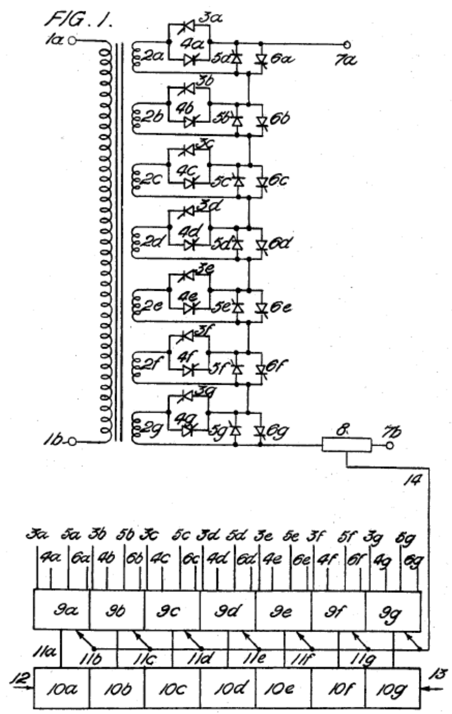


Figure 1-6 Thyristor based solid-state voltage regulator

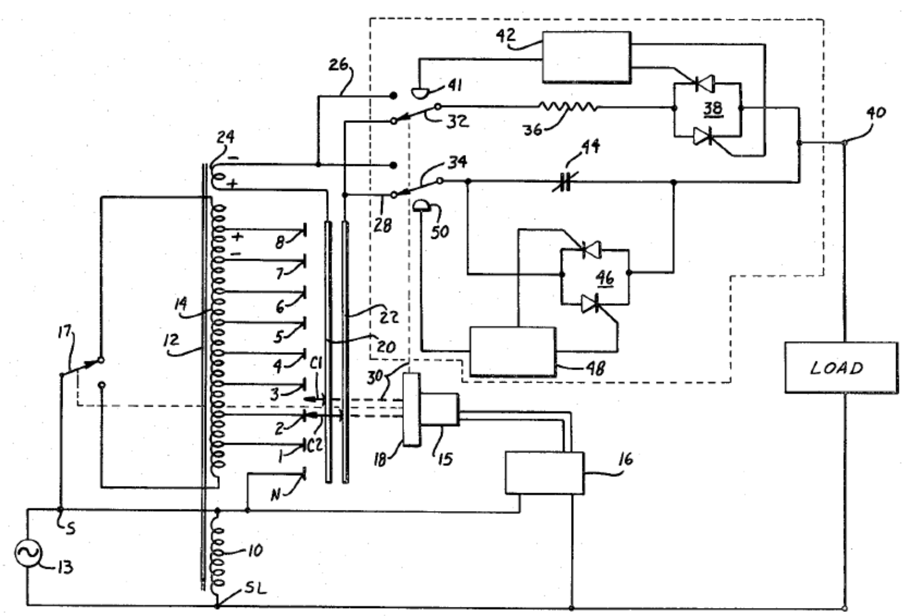


Figure 1-7 Auxiliary winding based arcless voltage regulator

The patent [11] from Siemens-Allis presented a topology with an auxiliary winding to eliminate arcing in Figure 1-7. The arcless procedure in movable contacts is helped by two pairs of anti-parallel SCRs to connect or disconnect with terminal 26 or terminal 28. The arcless switching process takes typically 4 seconds which is 100 times longer than conventional switching process with arcing. Besides, the SCRs should be always gated when the movable contacts are connected with terminal 26, which increase the power loss of the voltage regulator.

The patent [12] presented a rotary intermittent drive to support the arcless voltage regulator. This patent introduced a new gear drive mechanism into the conventional voltage regulator that makes the tap changing event more complicated.

The paper [13] is an improvement for On Load Tap Changers (OLTC) which has a similar working principle compared with the step voltage regulator. A hybrid diverter design in Figure 1-8 is proposed to eliminate the arcing. The operation speed can be faster than conventional voltage regulators due to the characteristics of IGBT. However, the

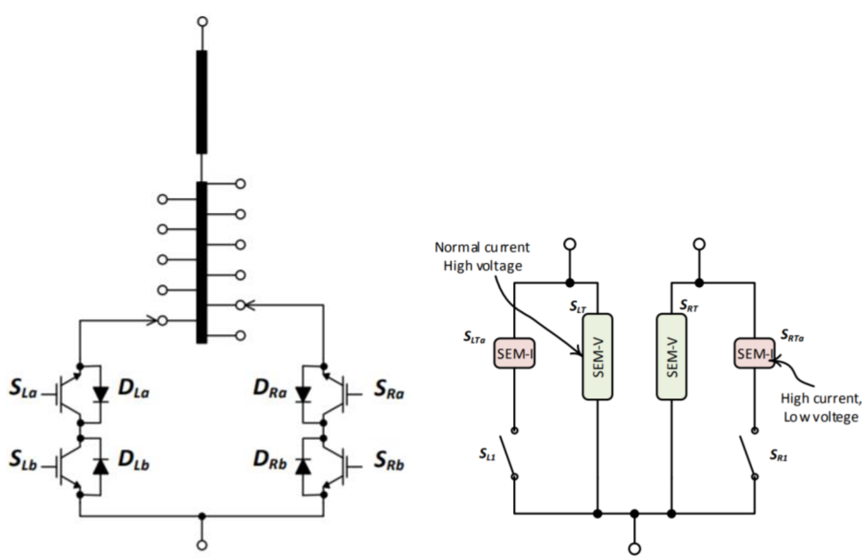


Figure 1-8 A hybrid power electronics of OLTC

IGBT is in series into the path in steady state condition, which increases the conduction loss of the voltage regulators. The cost of this topology can be increased because of the high cost of IGBT.

None of the previous solutions has been successfully commercialized so far due to various reasons, such as reliability, solution cost, safety and changes to the existing apparatus and control.

1.6 Organization of Thesis

Chapter 1: The first part of this chapter is the introduction of the step voltage regulator, including the mechanism introduction, working principle, short-comings of arc and advantages of arcless tap changer. A literature review of the state-of-the-art arcless approaches is also conducted in this chapter.

Chapter 2: A hybrid switch based topology of the arcless voltage regulator is proposed in this chapter. The schematic, working principle and gate and logic control approach are presented in detail.

Chapter 3: This chapter introduces the arcless voltage regulator model in Simulink. The simulation condition and simulation procedure are included to perform the arcless tap changing event. The simulation results are shown at the end of this chapter.

Chapter 4: This chapter introduces the hardware design procedure of arcless voltage regulator. This chapter also provides detailed information on PCB design and function explanations. The control realization is introduced in this chapter as well.

Chapter 5: This chapter shows the experimental bench setup and the experimental conditions. The experimental results are demonstrated and discussed.

Chapter 6: This chapter presents the conclusion of this hybrid switches based arcless voltage regulator, including the values of this approach and the future work for the improvement.

CHAPTER 2: A HYBRID SWITCH BASED ARCLESS VOLTAGE REGULATOR

2.1 Introduction

Traditional power distribution systems are penetrated by power electronics switches because of its numerous advantages, such as lower operation time, no arc during switching, no humming noise, etc. In this chapter, a hybrid switch based arcless voltage regulator is proposed to eliminate arcing. The hybrid switch consists of power electronics switching devices which are two anti-paralleled Silicon-Controlled Rectifier (SCR), and electro-mechanical devices which are electro-mechanical contactors. The advantage of this approach is to minimize the change of the existing step voltage regulator for easier manufacturing purpose in the future. The electrical operation time and lifetime of this voltage regulator will be significantly increased by eliminating the arcing in tap changing operation.

In this chapter, section 2.1 is a brief introduction of a hybrid switch based arcless voltage regulator. Section 2.2 introduces the schematic and advantages of this topology. Section 2.3 introduces the switching sequence of this arcless voltage regulator. Section 2.4 proposes a cost-effective SCR gating and control approach for the arcless voltage regulator.

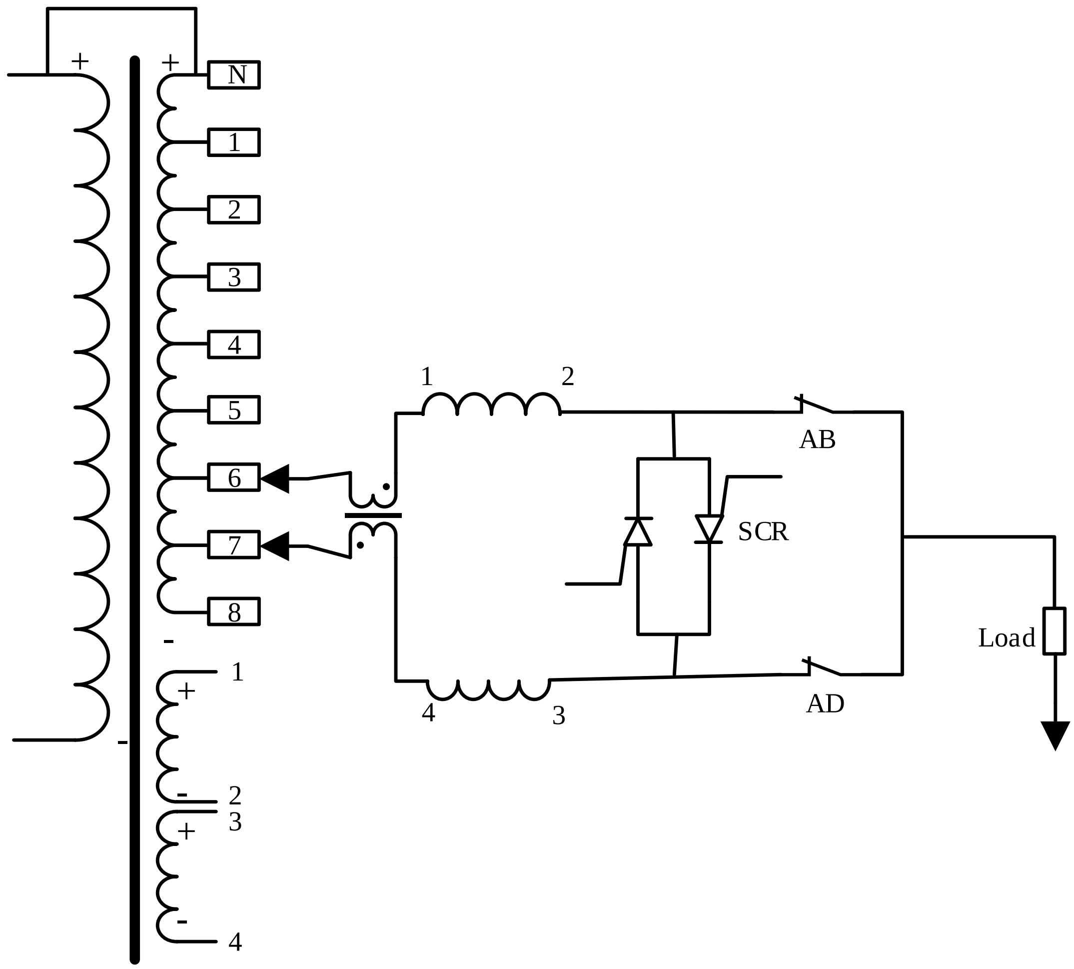


Figure 2-1 Schematic of hybrid switch based arcless voltage regulator

2.2 Schematic

Figure 2-1 shows the schematic of the hybrid switch based arcless voltage regulator. the autotransformer is on the left with nine stationary contacts on the series winding for voltage regulation. Two movable contacts are connected with stationary taps which can be slid up and down to change the output voltage. A bias transformer and an equalizer are in series into two paths to limit the circulating current. The hybrid switches include two anti-paralleled SCRs that are paralleled into two paths, as well as two electromechanical contactors which are in series with two paths. These switches are added to assist the step voltage regulator operating in an arcless way. The topology doesn't change too much from the original configuration of a step voltage regulator.

2.3 Working Principle

The basic operation principle is to use a hybrid switch, which has two antiparallel SCRs to provide a shunt current path to the electromechanical switches when a tap changing is initiated, then the current is interrupted by the SCR without arcing. As a result, there is no current flowing through the contact during the tap changing mechanism moving from one tap to an adjacent tap, so no arcing occurs and the arcless tap changing operation is achieved.

The detailed switching sequence of the proposed arcless tap changer is illustrated in Figure 2-2 and described below. The switching condition is the upper path moving from tap #6 to tap #7. The output voltage of the voltage regulator is decreased by 5/8 % of the input voltage.

Figure 2-2 (a): The initial condition is the two movable contacts of the tap changer are in taps #6 and #7. Current exists in both AB and AD paths, and SCRs are prepared to gate on (orange).

Figure 2-2 (b): The electronic controller sends the command to change the upper tap from tap #6 to tap #7. The contactor AB opens which generates a small spark voltage (12V initially). The voltage sensor detects the spark voltage and generates a gate signal to trigger the SCR at the same time. The condition for SCR triggering is I(AB) & I(AD) & V(SCR), meaning there are current conducting in both switch AB and AD, as well as a voltage drop crossing the SCRs. It should be noted that as soon as the SCR turns on, the load current will commutate from switch AB path to the SCR path. The spark voltage will be extinguished in the range of microseconds depending on the loop parasitic inductance. In contrast, the contact arcing time in traditional voltage regulators is in the range of milliseconds depending on the contact moving time between the taps. The contact wear from the sparking in this proposed operation is negligible because of the extremely short arcing time. The SCR momentarily assumes 1/2 of load current (red) and switch AD conducts full load current.

Figure 2-2 (c): After switch AB is opened, SCR gate signal is removed. The SCR turns off after one or two half cycles at the current zero crossing point. Then there is no current via the upper path, I(AB) = 0, all the load current is flowing via the lower path.

Figure 2-2 (d): The voltage regulator dial switch advances, so the upper contact moves from tap #6 to #7. There is no arcing occurs because there is no current flowing through the stationary contact and the upper path.

Figure 2-2 (e): Switch AB closes, immediately SCR gate signal is applied. SCR is gated and provides a current path in case AB contact bounces on closure. The condition for SCR triggering is the same that I(AB) & I(AD) &V(SCR). This will help extinguish the arcing caused from any contact bouncing.

Figure 2-2 (f): Current is now conducting in both upper and lower paths. SCR is not triggered because there is no voltage drop crossing the SCRs. The arcless tap changing operation from tap #6 to #7 is now achieved, and the SCR gate control is powered and ready in anticipation of the next tap changing operation.

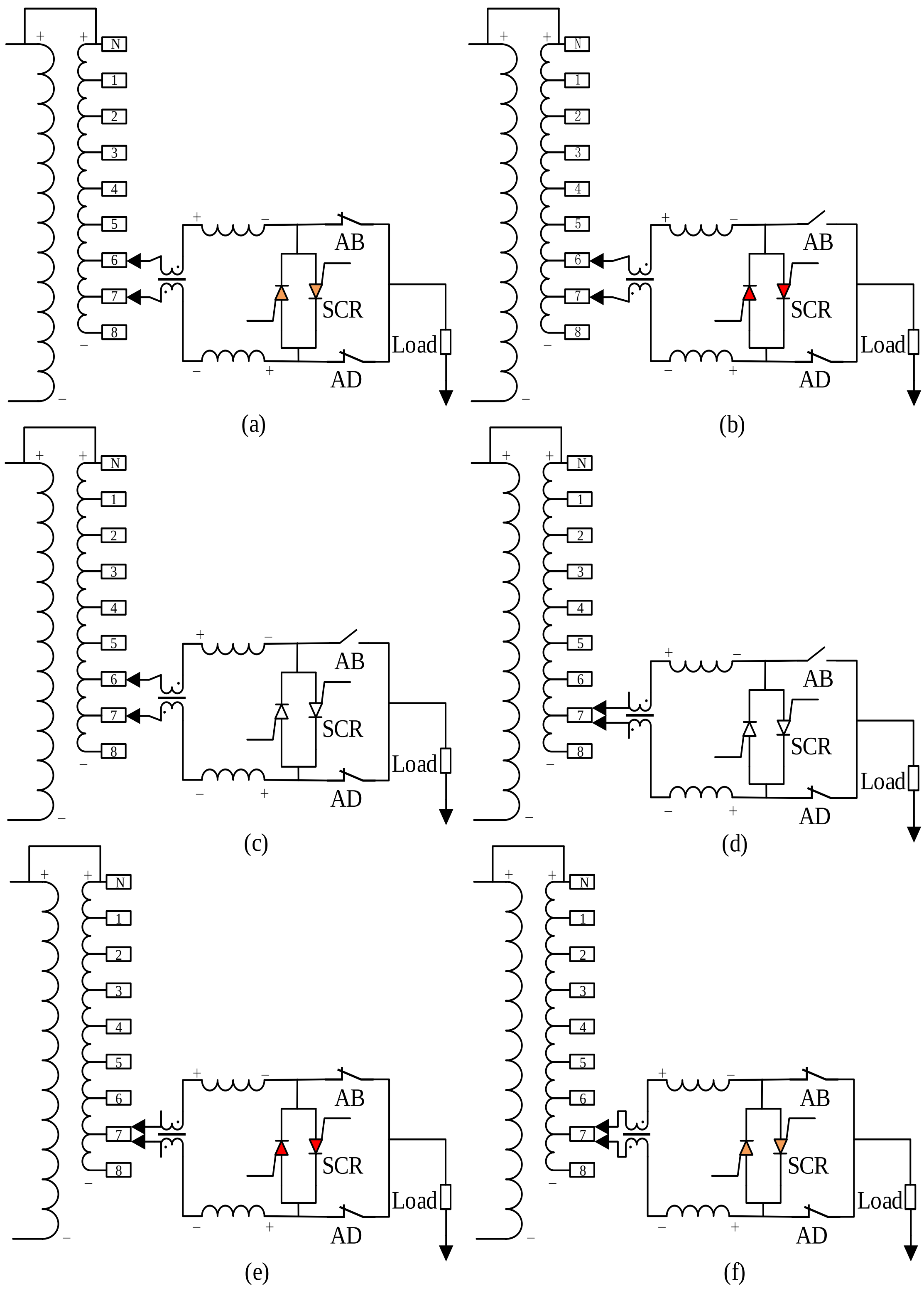


Figure 2-2 Switching sequence of Hybrid switch based arcless tap changer

2.4 SCR Gating and Control Approach

The gated approach in the literature review section requires continuous gate current flowing to the SCR when the load current flows through both auxiliary switches. There is a problem with this approach if the intended application needs to span a large current range. Further, the use of continuous, high-current gate control circuits in the previous approach requires that the rectified power for the control circuits needs to be filtered by large capacitors, such as electrolytic capacitors which are largely incompatible with the hot-oil environment of the regulator tank. Therefore, a new SCR gating approach is developed so that the current transformers (CT) turns ratio can be increased in order to have a range of manageable secondary currents and also have useful gate current.

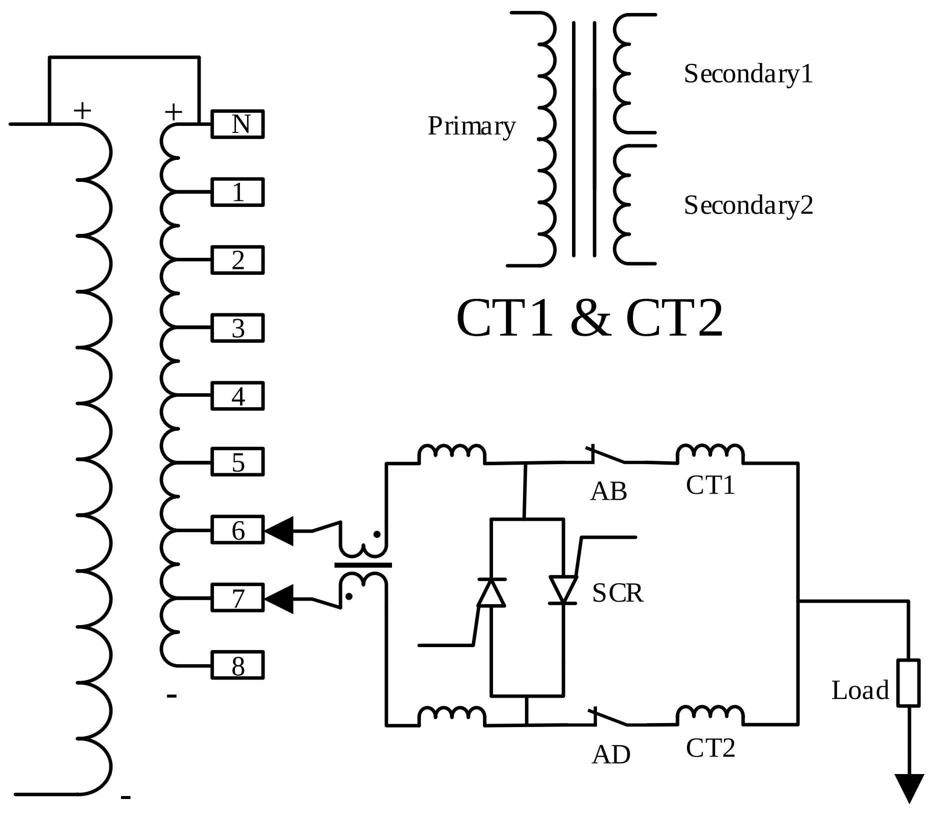


Figure 2-3 SCR based arcless tap changer and current transformer (CT)

This section introduces an SCR gating approach to use the low-cost current transformers (CT) for both current sensings and to provide power to the SCR gate. The CT itself serves as the isolated gate power supply. The CT current information and voltage across the SCR are utilized to decide when to turn on the SCR without the need of commutating to the electronic controller, therefore all the SCR controls are implemented locally to improve the reliability. Figure 2-3 shows the placement of two special current transformers (CTs). The primary side of these CTs is in series with the upper and lower path respectively. These CTs have dual secondaries and are used to both sense current and to provide power to gate the SCRs. The logic of I(AB) & I(AD) & V(SCR) is enabled by the contactor signal which is depicted in Figure 2-4. The anode voltage of each SCR is sensed, conditioned and applied to the logic gate. The SCR gate signal is generated when both CTs have current flow and positive voltage exists at the anode of the controlled SCR. The output signal from "AND" gate is delayed one or two half cycles and triggers the tap changer controller to drive the dial switch moving the contacts. The movable contact moves from one tap to an adjacent tap after the current is commutated to another path. The proposed gating and control approaches have the advantages of lowering power requirements for control components with lower cost.

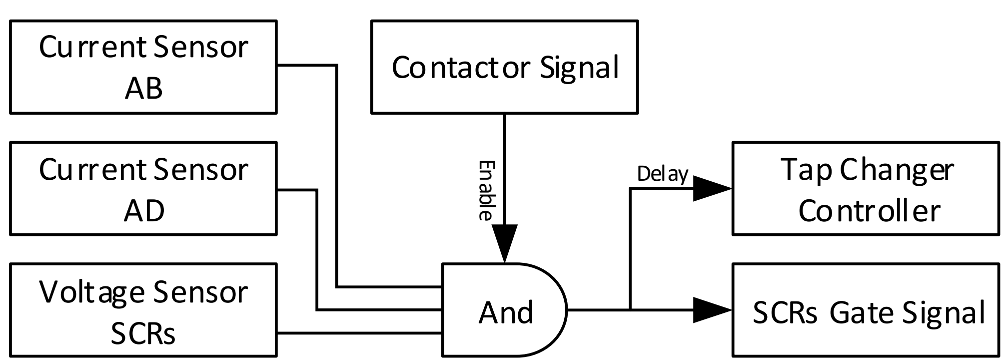


Figure 2-4 SCR gating and control logic

CHAPTER 3: SIMULATION DESIGN AND RESULTS

3.1 Introduction

In this chapter, a simulation is implemented to validate the proposed arcless voltage regulator. Section 3.1 introduces the simulation building procedure and the simulated condition of the arcless voltage regulator. Section 3.2 lists the simulation parameters. Section 3.3 includes the simulation results and the comments and discussion based on the results.

The simulation environment is in MATLAB Simulink. The simulation is a medium-voltage step voltage regulator that shows in Figure 3-1. A transformer block that connected the primary side and secondary side together as an autotransformer. The secondary side is split into 8 sections and connected with 9 notes as the stationary taps in the tap changer mechanism. Inductor 1 and inductor 2 are in subtractive polarity as an equalizer to limit the circulating current in the AB path and AD path. Breaker 1 and breaker 2 are working as two contactors in AB and AD path. The tap changer is connected with an R-L load.

The simulation conditions are the same as the switching procedure in Figure 2-2 that are listed below:

1) The movable contacts move from bridging position (on tap #6 and #7) to symmetrical position (on tap #7)
2) The condition for SCR triggering is I(AB) & I(AD) &V(SCR).

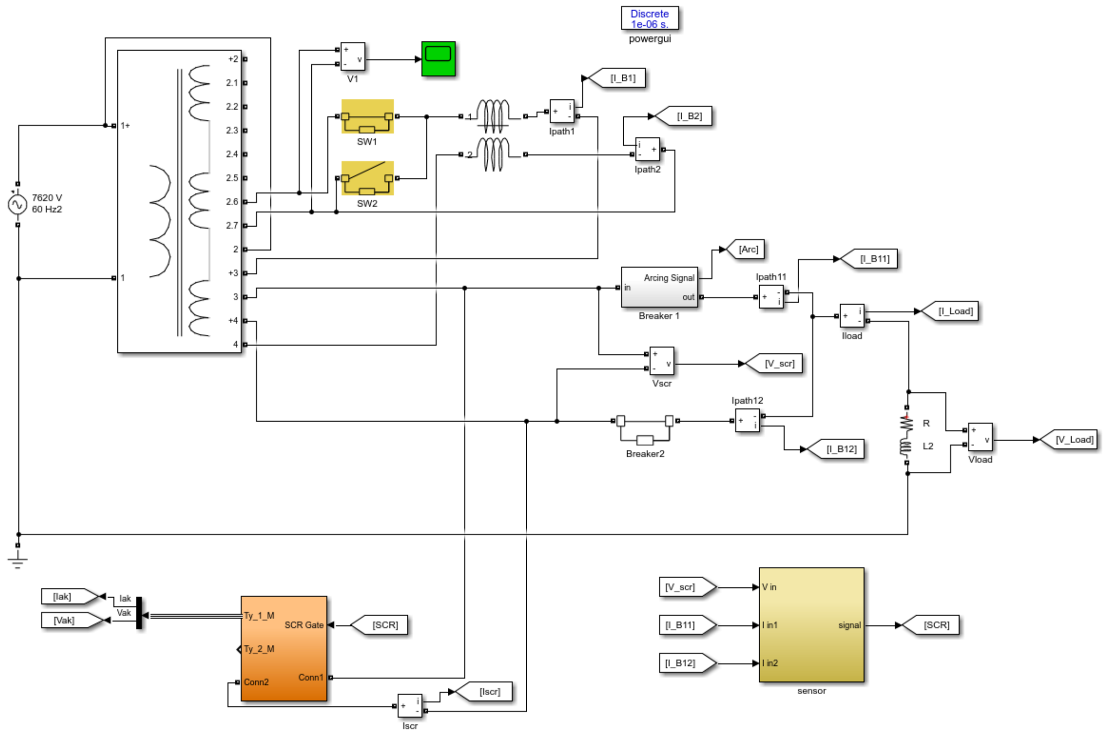


Figure 3-1 Simulation of arcless voltage regulator in Simulink

Since the simulation condition is moving the movable contact tap #6 to tap #7, only the AB contactor needs to be triggered during the simulation. Thus, the arc model is designed in breaker 1 to simulate the arcing procedure during the tap changing event. The arcing procedure is very short because the arc voltage will transfer the current flowing from the AB path to the SCR path once the arcing is detected. Therefore, a DC source with the inversed direction of current is introduced in series with the Breaker 1 to simulate as an arc voltage.

SW1 and SW2 are two switches for simulating the movable contacts moving from one tap to another. The Breaker 1 block simulates an arc when the contactor AB starts to open.

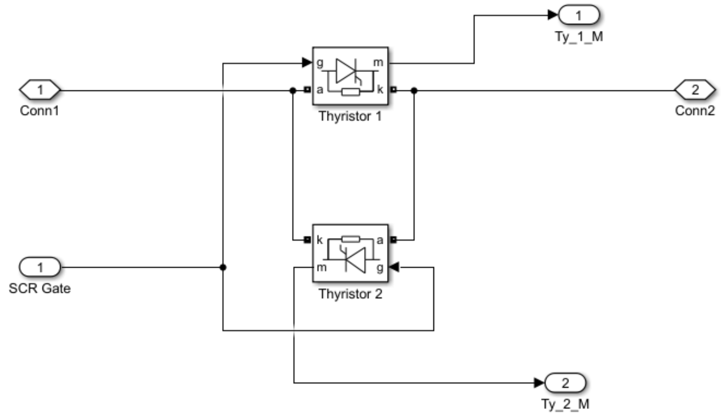


Figure 3-2 SCRs block (bottom left block in Figure 3-1)

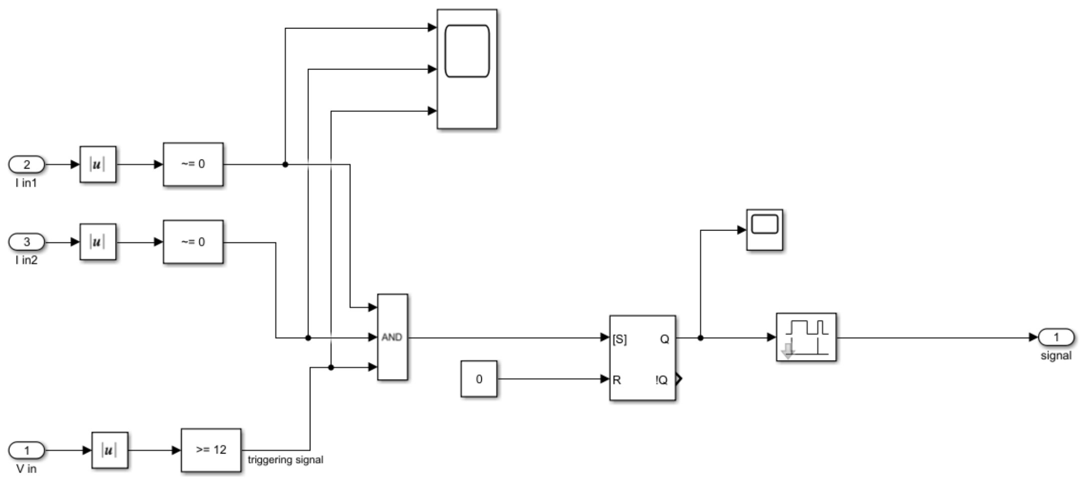


Figure 3-3 SCRs logic control block (bottom right block in Figure 3-1)

The bottom left subsystem block in Figure 3-1 is the anti-parallel SCRs which is in parallel between AB path and AD path. Figure 3-2 shows the details of this subsystem block.

The bottom right subsystem block in Figure 3-1 is the logic block to trigger the SCR via all of the input signals to meet the requirements. The logic chain in the subsystem shows in Figure 3-3. The logic shows that both I(AB) and I(AD) should not be zero, while the arc voltage is larger than 12V. The constraints of I(AB) and I(AD) are designed for the purpose of protection, that will not be triggered by mistake to cause the short circuit in tap changers. The simulation results and analysis will be presented in this chapter later.

The breaker control block is a unit-step signal to start the tap changing event. In this case, the tap changing starts in 0.5 s.

3.2 Simulation Parameters

The simulation is a medium-voltage step voltage regulator that input voltage is 7620 Vrms, 60 Hz. The secondary side is 871 V total. The tap voltage is 5/8 percent each. The Table 3-1 lists the component values used in the simulation.

Table 3-1 Major parameters of tap changer simulation

Component	**Symbol**	**Value**
Nominal power of transformer	P_n	677.3 kVA
Nominal frequency of transformer	f_n	60 Hz
Primary voltage	$V_{p, rms}$	7,620 V
Voltage between each tap	V_{tap}	871/8 V
Equalizer winding	L_{eq}	117.5 uH
Load current	I_L	875 A
Load inductance	L_{load}	0.014 H
Load resistance	R_{load}	7 Ω
Power factor	Pf	0.6978

3.3 Simulation Results

The simulation works in several working conditions to validate the feasibility of the hybrid switch based arcless voltage regulator. The initial conditions for all the cases are the same: that the tap position in 0 s is the upper movable contact (AB path) in Tap #6 and the lower movable contact (AD path) in Tap #7, AB path and AD path share a current at the bridging position. SCRs are prepared to gate on. The moving event is boosting a one-step voltage, which moves the AD path from tap #6 to tap #7. The specific working conditions are listed below in Table 3-2.

Table 3-2 Simulated working conditions of the arcless voltage regulator

# of Case	**Working Conditions**
1	Common Case (Tap changer triggered at 0.5 s)
2	Tap changer triggered at the peak value of the load current
3	Tap changer triggered at the zero-crossing point of the load current
4	The 5^{th} order harmonics 5% is applied to the input

3.3.1 Case #1

Case #1 is the common case to trigger the voltage regulator operation. Figure 3-4 shows the simulation result of this arcless step voltage regulator. Tap changer is triggered at 0.5s.

In 0.5s, the controller sends a command to tap changer which moves AB path from Tap #6 to #7. Switch AB starts to open and generates a spark voltage (12V initially) to trigger gate signal of the SCR. The triggering condition for SCR is I(AB) & I(AD) & V(SCR). After the SCR turns on, the current commutates from contactor AB to SCR.

In 0.503s, current in SCR decreases to zero which means the SCR turns off. Switch AB fully opens. Current in AB path becomes zero.

In 0.55s, AB path starts moving away from Tap #6 to #7. Since AB path current becomes zero before the moving, the AB movable contact can move without arcing.

In 0.583s, AB path connects to Tap #7. Switch AB closes. The SCR is triggered to avoid arcing from any contact bouncing. AB path successfully moves from Tap #6 to #7. AB path and AD path share a current at the symmetrical position. SCRs gate control is ready for the next switching command.

According to the simulation results, the arcless operation is achieved with the proposed control method. The total arcless switching event takes 83 ms in the simulation.

3.3.2 Case #2

Case #2 is the condition the tap changer is triggered at the peak value of the load current. The power factor is calculated by the load impedance. According to the power factor, the triggering time at the peak value of the load current can be calculated.

Figure 3-5 depicts the simulation results of Case #2. The triggering time is 0.5063s. The tap changing sequence and SCR triggering procedure are the same as the switching sequence described in section 3.3.1.

3.3.3 Case #3

Case #3 is the condition the tap changer is triggered at the zero-crossing point of the load current. The power factor is calculated by the load impedance. According to the power factor, the triggering time at the zero-crossing point of the load current can be calculated.

Figure 3-6 depicts the simulation results of Case #3. The triggering time is 0.5021s. The tap changing sequence and SCR triggering procedure are the same as the switching sequence described in section 3.3.1.

3.3.4 Case #4

In this section, 5% 5th order harmonic is introduced into the input voltage source to detect the effect on the controller design. The magnitude of a harmonic is reduced with the increase of its order. Therefore, the low order harmonics have a larger magnitude compared with high order harmonics. The low order harmonics may cause some resonance conditions which is dangerous for the system in some situations. That is the main reason for adding a 5th order harmonic to the input source.

Figure 3-7 depicts the simulation results of Case #4. The triggering time is 0.5 s. The tap changing sequence and SCR triggering procedure are the same as the switching sequence described in section 3.3.1.

3.3.5 Conclusion

All the simulation results show the topology can be applied to the conventional voltage regulator to eliminate the arcing. The current in one path can be commutated to another path assisted with the SCRs and contactors without the arcing. The simulation works in different cases to make sure the control logic design is suitable for the different corner conditions. The simulation results indicate the feasibility of the hybrid switch based topology of the arcless voltage regulator

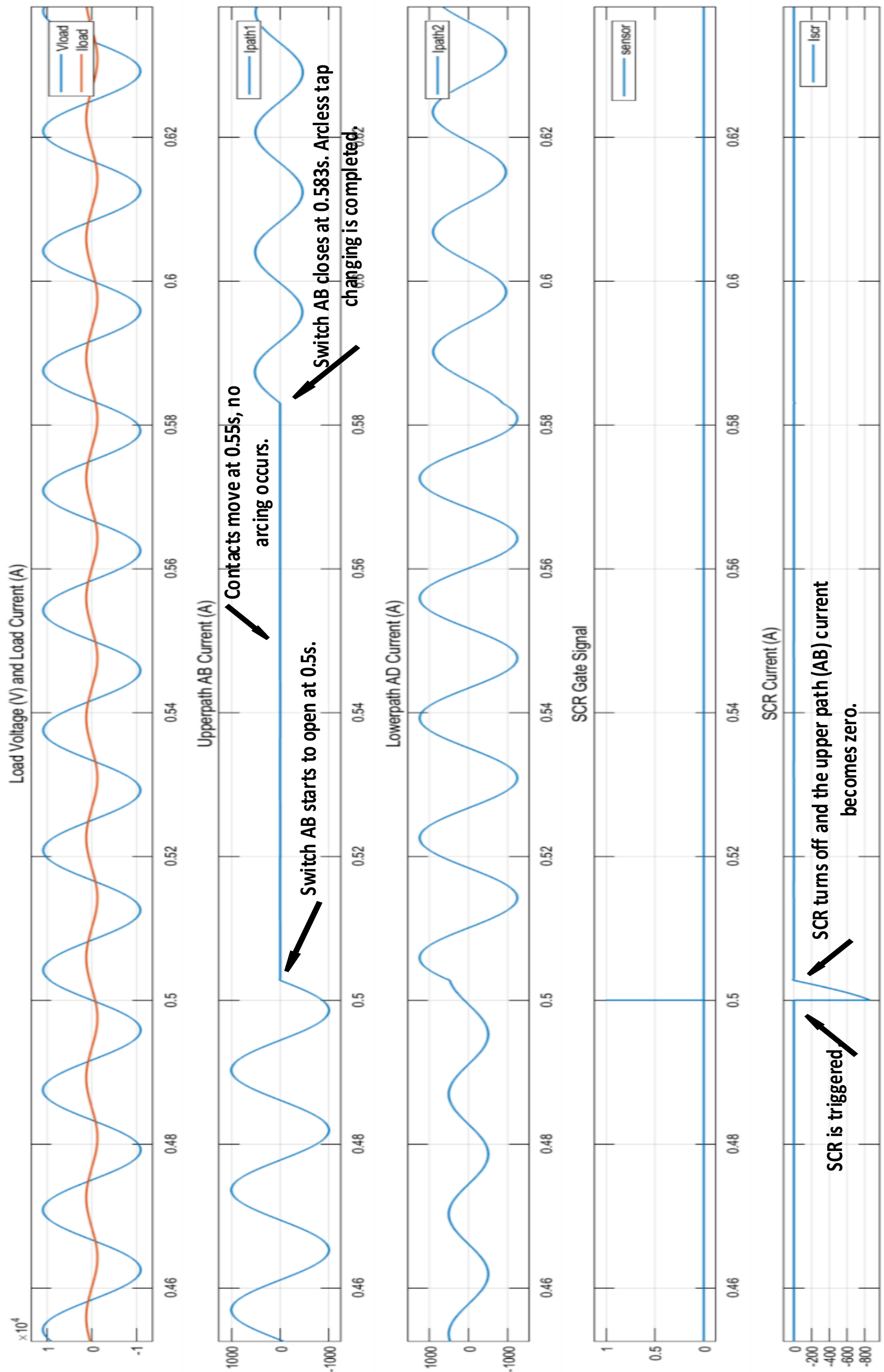


Figure 3-4 Simulation results (Case #1)

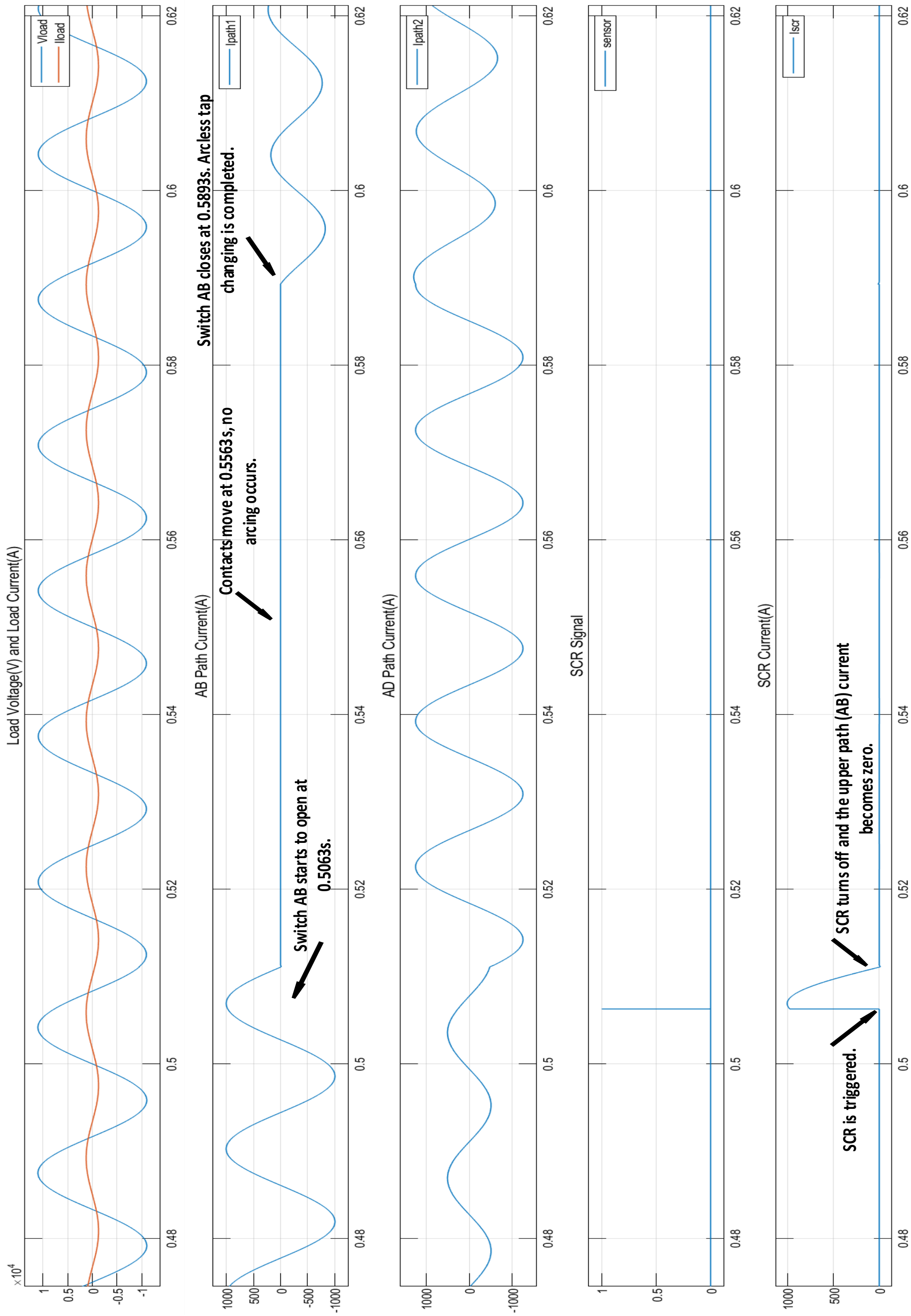


Figure 3-5 Simulation results (Case #2)

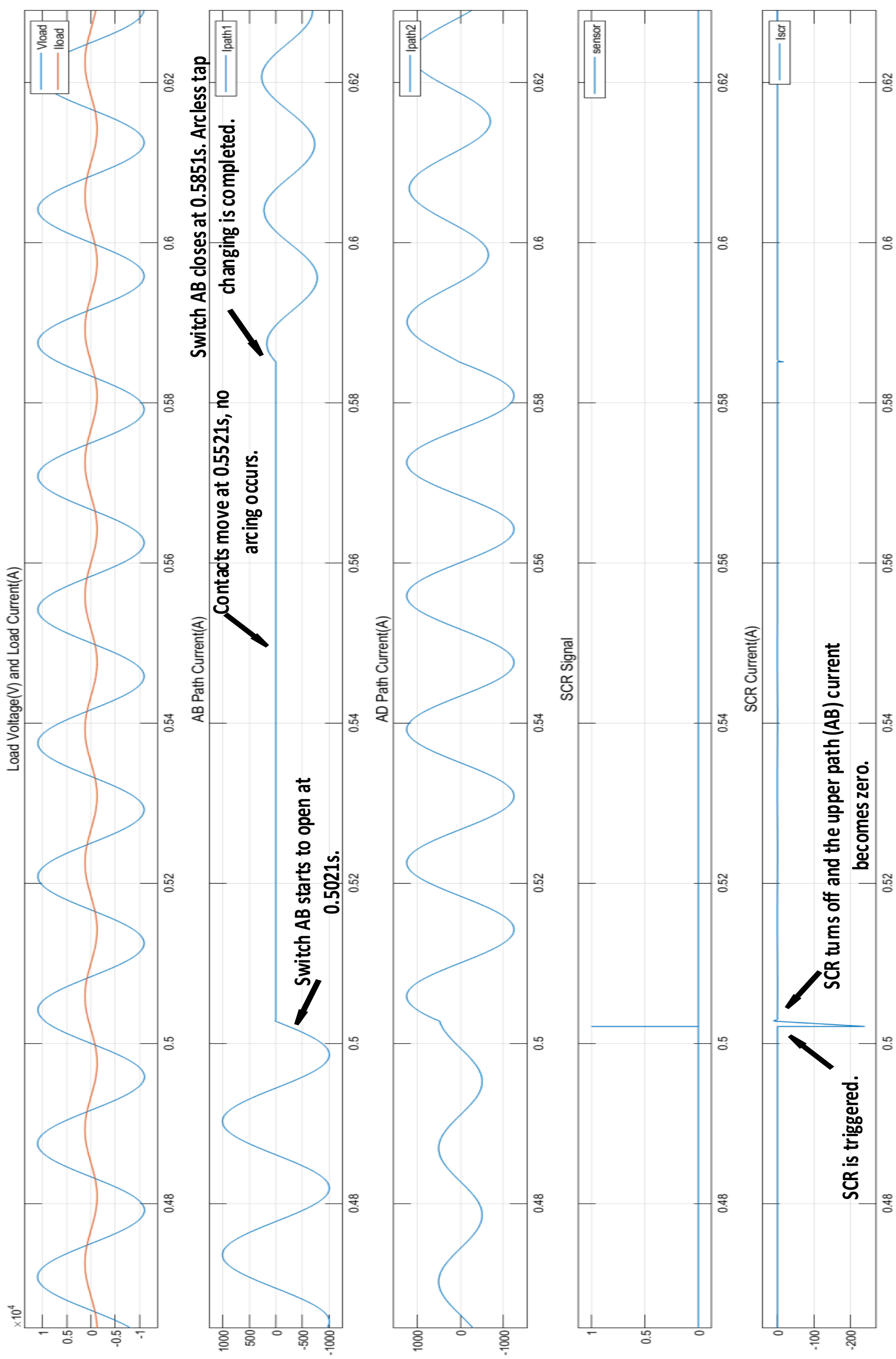


Figure 3-6 Simulation results (Case #3)

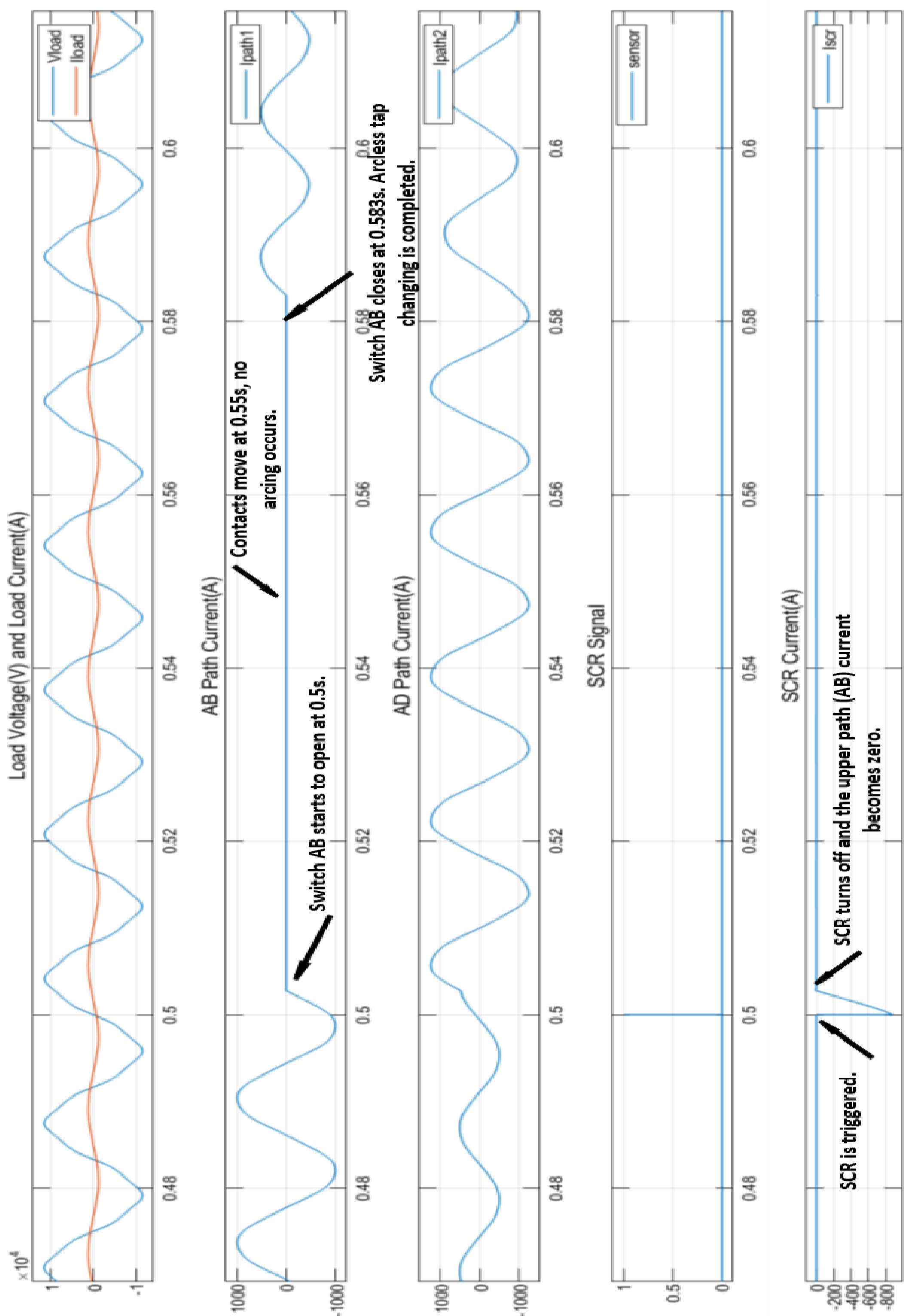


Figure 3-7 Simulation results (Case #4)

3.4 Thermal Simulation

The thermal simulation is implemented in PLECS for analyzing the SCR device. Since the operating time of SCRs in a tap changing event is very short, the current through the SCR can be seen as a pulse. The SCR rating could be smaller compared to a continuous operation SCR, which decreases the total cost of the arcless voltage regulator.

The simulation environment is in PLECS. The voltage signal and current signal are communicated from Simulink into PLECS. The thermal characteristics are built up in a PLECS thermal model according to its datasheet.

The thermal simulation result is shown in Figure 3-8. The ambient temperature is 25 ℃. The tap changing starts at the worst case that the half cycle of the path current goes through the SCR. The case temperature increases to 30.2 ℃ quickly and then decays to 25 ℃ which is the ambient temperature.

According to the simulation result, the temperature rise is far less than the maximum temperature of the device which means the rating and size of the SCRs can be further reduced, and consequently reduce the cost of this hybrid switch based arcless voltage regulator. Further investigation will be conducted to determine the optimal rating of the SCR in this application.

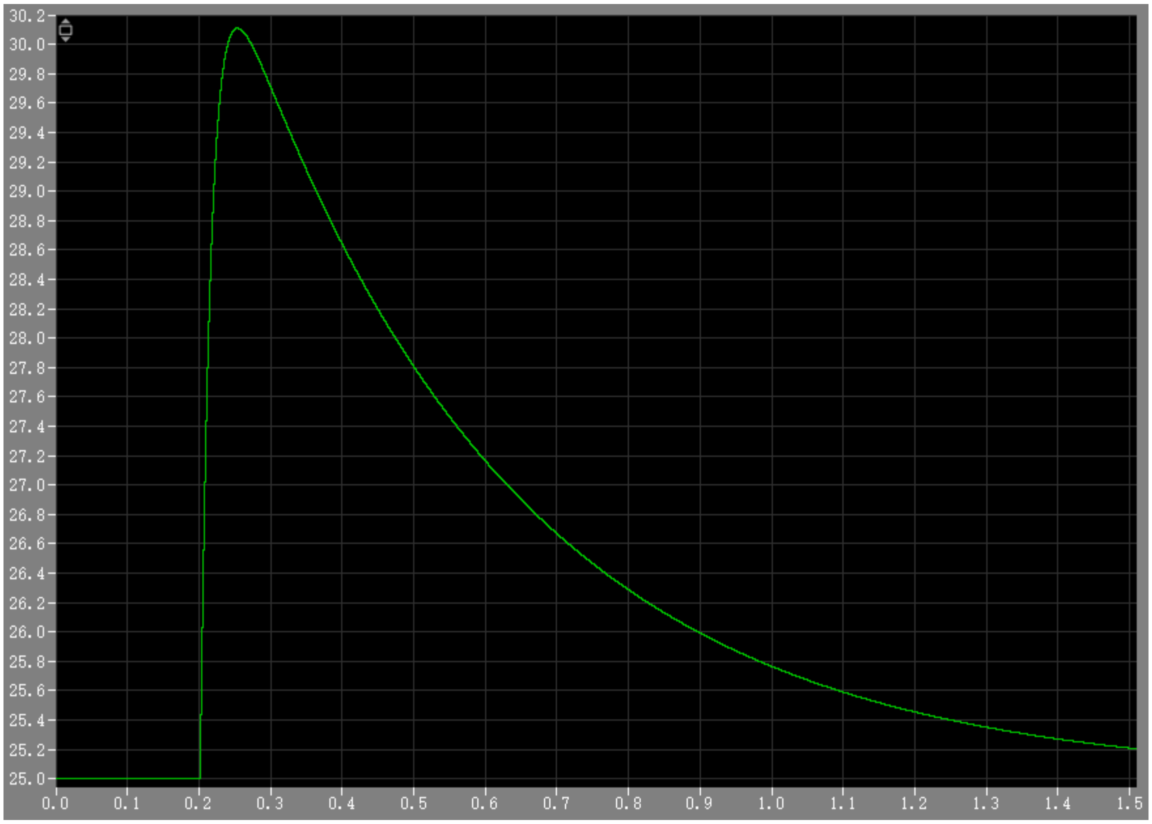


Figure 3-8 Thermal simulation

CHAPTER 4: HARDWARE DESIGN

4.1 Introduction

In order to validate the arcless simulation in Chapter 3, a 12 kVA hybrid switch based arcless step voltage regulator is developed in this chapter. The designed input voltage is 240 V for easy implementation in the lab environment. The lab transformer has five stationary taps in the secondary side including the natural tap.

The blueprint of hardware design shows in Figure 4-1. The rating of the autotransformer is also shown in the figure. A tap changing command can trigger the AB or AD contactor via the Digital Signal Processor (DSP) and the interface board. The current of AB and AD path and SCR voltage are sensed from the voltage sensor and current sensors as the input signals to the interface board. The interface board can process the signals from

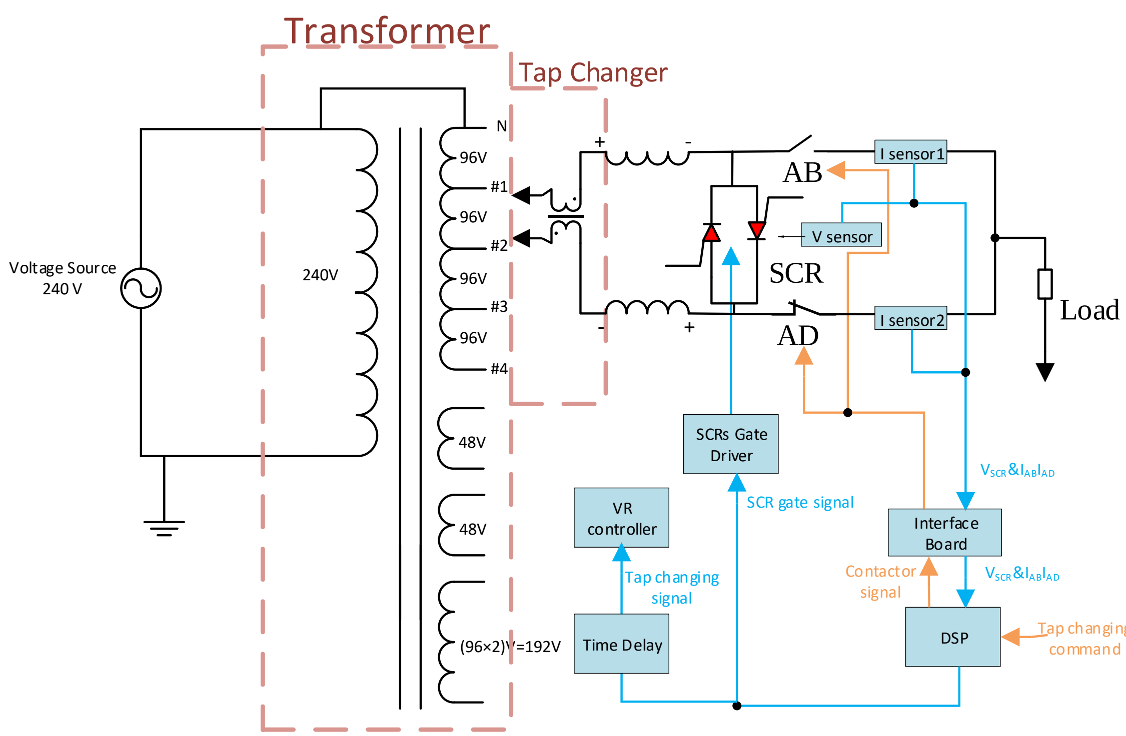


Figure 4-1 Design blueprint of arcless voltage regulator

the sensors to become the signals which have suitable voltage levels to connect with the DSP input pins. After the processing, the input signals are processed by the DSP with the logic design. DSP can generate a signal to trigger the SCRs and the voltage regulator controller for the tap changing operations. The SCR gate signal can turn on the SCRs, while the tap changing signal can trigger the dial switch to move the contacts to step up or step down the load voltage. The Voltage regulator (VR) controller is a programmable control box to control the tap changer mechanism.

4.2 Printed Circuit Board Design

A Printed Circuit Board (PCB) is designed to combine the interface board and all the gate drive sections to compact the hardware size and save spaces and wires. First of all, 5V is determined as the input voltage for all of the circuits in the PCB. Each circuit needs to convert the 5V input voltage to its desired voltage level. All the headers are selected to have a friction lock fastening type to make sure there is a better connection during the experiment.

The PCB schematic of this arcless voltage regulator is shown in Figure 4-2. It consists of several main circuits: SCR gate drive circuit, contactor coil drive circuit, voltage measurement circuit, current measurement circuit and interface circuit.

SCR Gate Drive Circuit: Receive the triggering signal and trigger the anti-parallel SCRs to commutate the current from one path to another.

Contactor coil drive circuit: The contactor coil is controlled by AC voltage. Thus, a relay for controlling the coil circuit loop is designed in this PCB to open or close the contactor.

Voltage Measurement Circuit: Measure the voltage between anode and cathode of SCRs and feedback it to the DSP.

Current Measurement Circuit: Measure the current through AB path and AD path. Process the signal from the current sensor and transfer the current signals to the DSP.

Interface Circuit: Process signals from DSP. Amplify the signal to trigger the VR controller. Or process the signals from sensors to become proper signals for DSP input.

The input voltage for this PCB is 5V. In Figure 4-2, the A1 section is voltage source to step up the 5V to become 12V or ±12V for different purposes. C4 and D4 sections are the headers configuration for connecting to DSP and controller. The black and red blocks are test pins for testing and debugging the PCB. The capacitors paralleled between positive inputs or outputs and ground maintain the voltage level and filter the noise from the source side or the load side. These will not be explained in the later sections.

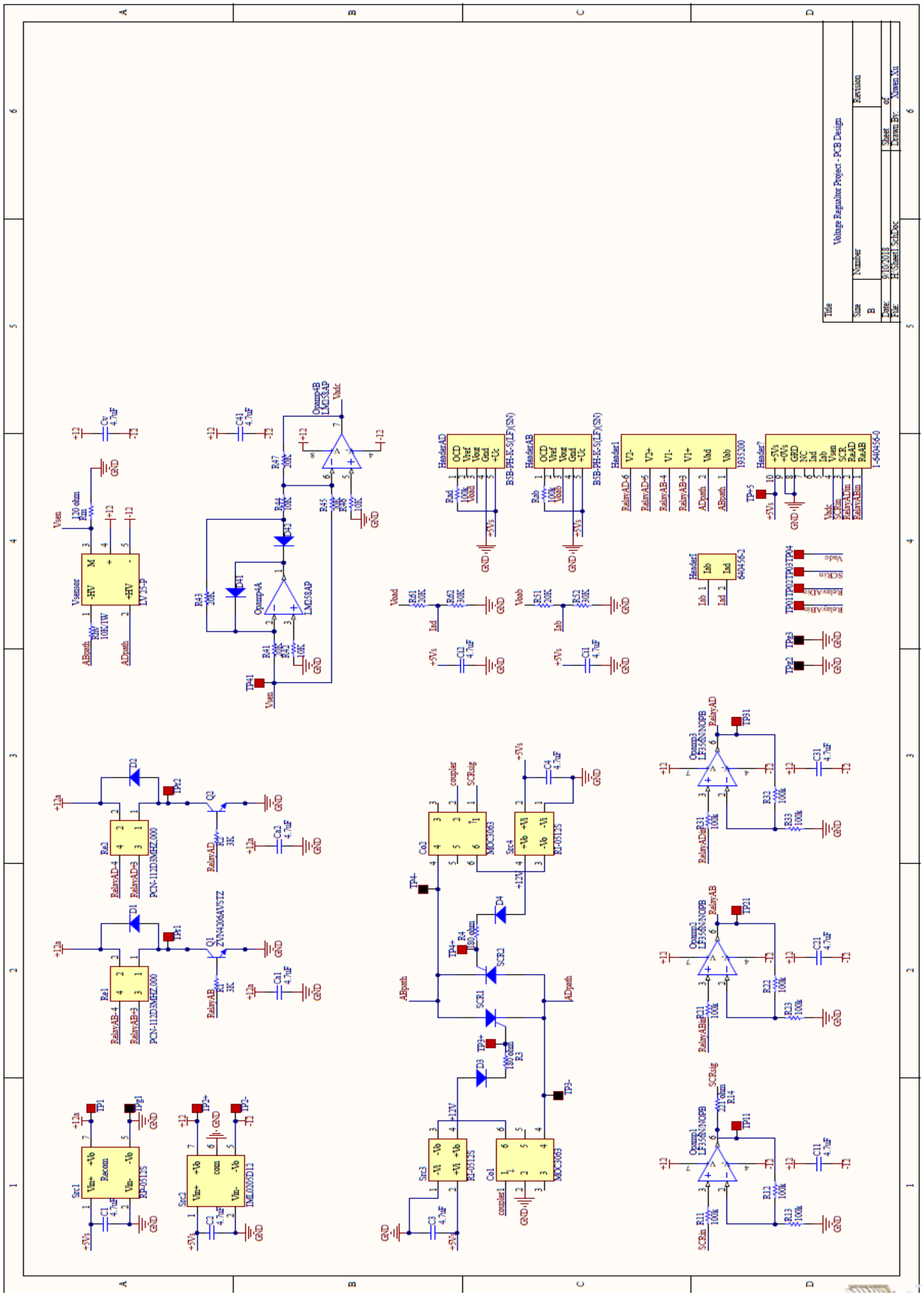


Figure 4-2 PCB schematic

4.2.1 SCR Drive Circuit

The SCR gate drive circuit design shows in Figure 4-4. Two isolated voltage sources (RI-0512S) are in the design for providing the gate drive power. Two photocouplers (PS2501-1-A) are the switches to trigger the SCR gate drive circuit. It also isolates the voltage overshoot from power side (movable contacts) to PCB side to prevent the voltage disturbance which may do damage to the PCB.

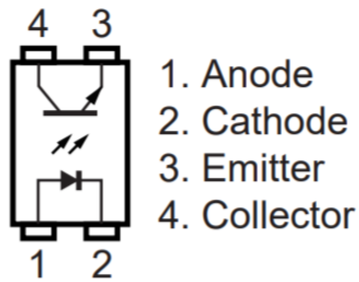


Figure 4-3 Photocoupler (PS2501-1-A) Schematic

The working principle of this circuit is introduced here. SCR triggering signal is detected by two photocouplers. The current flows from node 1 to node 2 in Figure 4-3. The LED produces an infra-red light to a semiconductor photo-sensitive device that is used to detect the emitted infra-red beam. The semiconductor device turns on after the detection. Then, a current flowing from the gate pin to cathode pin is provided by the SCR gate circuit. The condition to trigger the SCR are listed below:

1) There is a voltage drop from the anode to cathode of the SCR;
2) Triggering current is flowing through the gate to the cathode of SCR.

According to the triggering condition of SCR, the flowing current are both in SCR1 and SCR2 when a triggering signal is given to the circuit. But the voltage drop between the AB path and AD path forces that only one of the SCRs can be turned on when it has a triggering signal.

The SCRs (TYN840RG) triggering current sensitivity is 35 mA. The current flowing in the circuit loop is,

$$I = \frac{12V - 0.3V - 1V}{180\Omega} = 59.44\,mA$$

In this equation, 0.3V is a voltage drop of the photocoupler. 1V is a voltage drop of the diode. The sensitivity current of the selected SCR is 35 mA. Thus, the current calculated ablove can trigger the selected SCRs to conduct the circuit.

4.2.2 Contactor Coil Drive Circuit

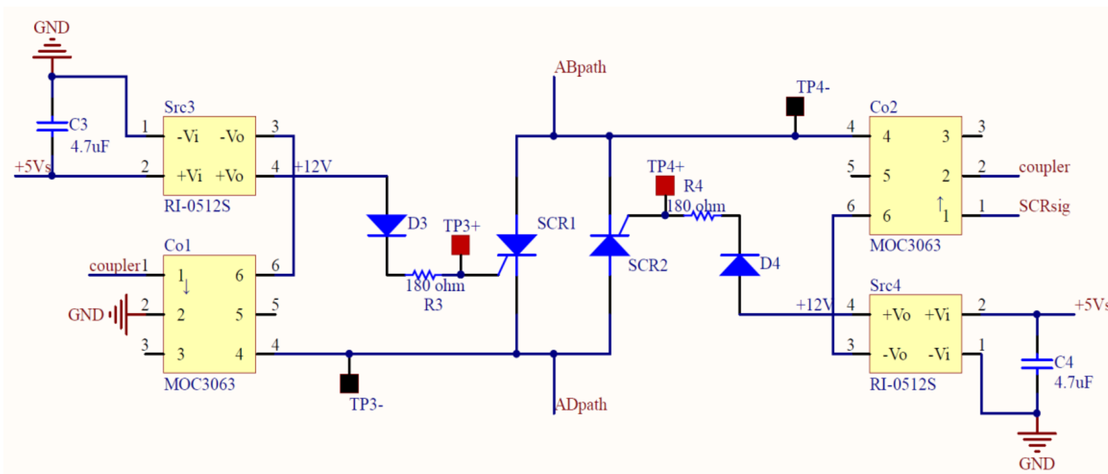


Figure 4-4 SCR gate drive circuit

A contactor (Figure 4-5) is an electrically-controlled switch used for switching an electrical power circuit [1]. In this design, the contactor should cut off the voltage between two adjacent stationary contacts, which is 96 V. The voltage requirement of the controlled circuit is 24 V AC. A fast-reacting relay is introduced in the circuit to break the controlled circuit to switch off the contactor.

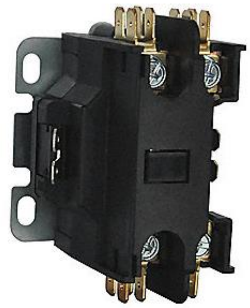


Figure 4-5 Contactor

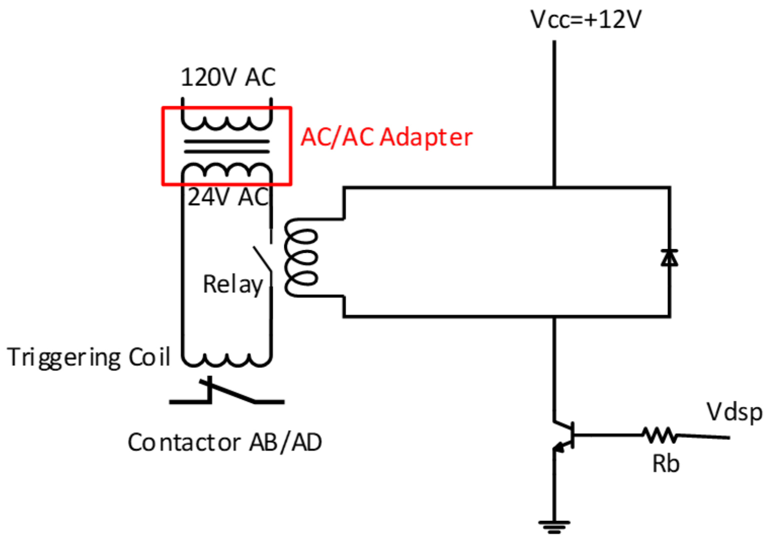


Figure 4-6 Schematic of contactor coil control circuit

The schematic is shown in Figure 4-6. There is an AC/AC adapter to step down the voltage from 110V AC in the outlet to 24 V AC in order to energize the coil on the contactor. The relay is in series with the controlled circuit of the contactor. Once a DSP signal is applied to the circuit. The relay gate drive is triggered to switch on the relay. After the relay switches on, the triggering coil is energized by a 24V AC. Then, the contactor switches on because of the powered triggering coil.

4.2.3 Voltage Measurement Circuit

The voltage measurement circuit consists of an LV25-P voltage sensor (Figure 4-7) and its surrounding circuit. According to the datasheet of this voltage sensor, the current ratio of the primary side to the secondary side is 10:25. Since the maximum input voltage is 100V and maximum input current is 10 mA, the Rhv can be derived from the equation below,

$$R_{hv} = \frac{100V}{10\ mA} = 10\ k\Omega$$

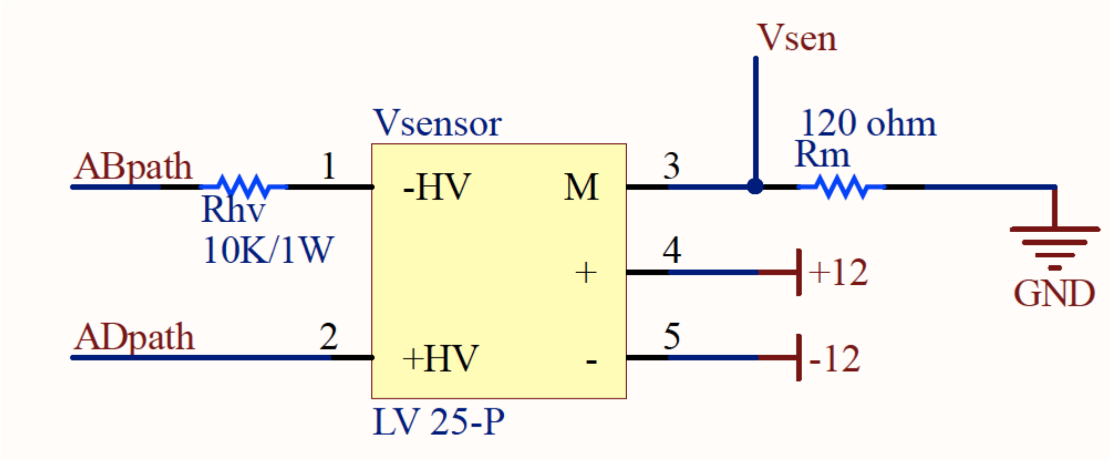


Figure 4-7 Schematic of voltage sensor

Since the maximum output voltage is required to be 3 V as an input voltage to DSP directly, the measurement resistor Rm is calculated below,

$$R_m = \frac{3V}{25mA} = 120\ \Omega$$

Due to the input voltage range for DSP is 0V~3V, an absolute circuit should be implemented after the voltage measurement. The absolute value circuit contains two op-

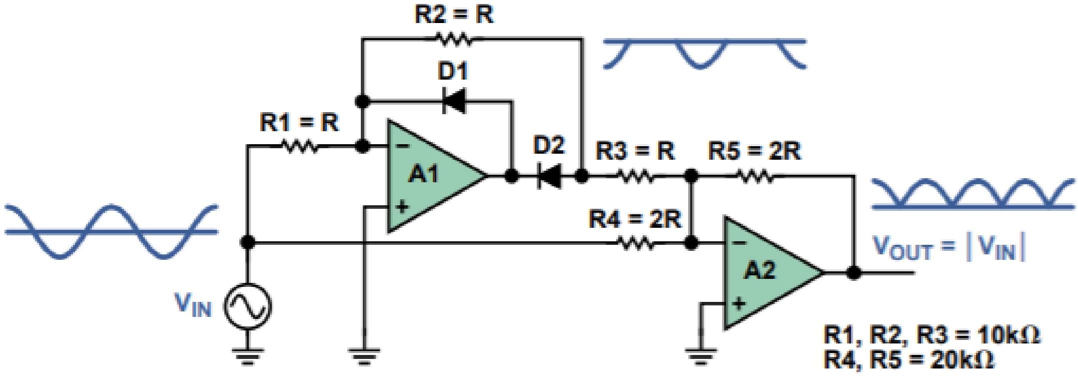


Figure 4-8 Absolute value circuit [23]

amps, two diodes and five precision resistors in Figure 4-8. When the input signal is positive, the output of A1 is negative, so D1 is reverse biased. D2 is forward biased, closing the feedback loop around A1 through R2 and forming an inverting amplifier. A2 sums the output of A1 times a gain of −2 with the input signal times a gain of −1, leaving a net gain of +1. When the input signal is negative, D1 is forward biased, closing the feedback loop around A1. D2 is reverse biased and does not conduct. A2 inverts the input signal, resulting in a positive output. Thus, the output of A2 is a positive voltage that represents the absolute value of the input, whether positive or negative [23].

After the absolute value circuit, the voltage measurement signal can go into the DSP directly as an input signal.

4.2.4 Current Measurement Circuit

Two current sensors, I sensor 1 and I sensor 2 in Figure 4-1, are detected the current of AB path and AD path respectively. The current sensor (LEM HO 50-S) can convert the current into a scaled voltage value that can be measured in its output side. According to the datasheet of LEM HO 50-S, the range of output voltage is 0V~5V. Thus, two precision resistors are connected in series with the output pin as a voltage divider to scale down the voltage range to be 0V~3V in order to transfer the current signals to DSP. The current sensors are only for zero crossing detection. Therefore, the current sensors don’t need a high precision characteristic.

4.2.5 Interface Circuit for the DSP

The purpose of the interface circuit is to scale up the DSP digital output voltage, which is 3.3 V DC, to an expected voltage level to trigger the SCR drive circuit and the

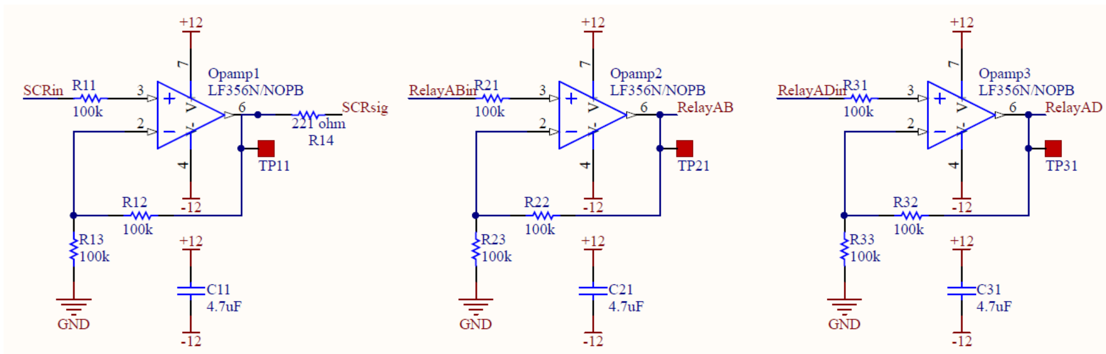


Figure 4-9 Schematic of the interface circuit

contactor drive circuit. Since the maximum output current of DSP is 9 mA, the output power of each pin is not enough to trigger the drive circuit directly. The interface circuit provides an extra power for both SCR drive circuit and contactor drive circuit.

Figure 4-9 is the schematics of the interface circuit. There are three non-inverting op-amp circuits to step up the voltage of input signals. These three output voltage values have the same mathematic relationship to the input voltage signals, which is,

$$V_{out} = \left(1 + \frac{100k}{100k}\right) * V_{in} = 2 * V_{in}$$

The output voltage is 6.6 V from the non-inverting op-amps and the output current will be not limited within 9 mA. The output signals from op-amps can trigger the drive circuits directly.

4.3 DSP Logic Design

An F28379D DSP is introduced in this section to complete the control process of arcless voltage regulator. The Delfino F28379D controlCARD (TMDSCNCD28379D) from Texas Instruments (TI) is a high-performance 180-pin microcontroller (MCU) and

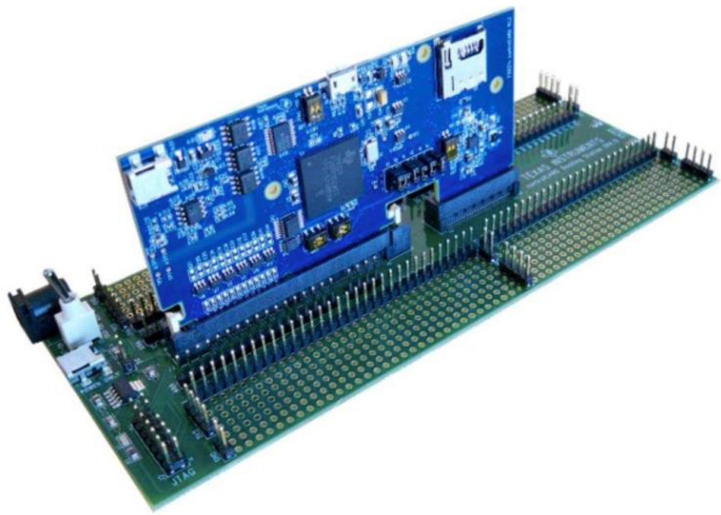


Figure 4-10 F28379D experimenter’s kit

shows in Figure 4-10. It is intended to provide a well-filtered robust design which is capable of working in most environments. The controlCARD contains connectors that allow the user to experiment with USB, a microSD card, and isolated UART/SCI with the F2837x MCU. A hi-density connector is also provided to experiment with external memory. Most GPIO, ADC and other key signals routed to hard gold connector fingers. The board has a single 5V input supply powers and an on-CARD 3.3V LDO. All MCU inputs are then decoupled using LC filters near the device [24].

A TI C2000 support package is installed in MATLAB Simulink to support the communication between Simulink and F28379D controlCARD. The TI C2000 support package provides some blocks to build up a block interface connection to communicate with F28379D. These blocks can be connected with most of the blocks in Simulink to complete the control design. The block diagrams can be compiled to C language automatically via embedded coder in Simulink and downloaded into DSP controlCARD directly. The communication blocks are listed in Figure 4-11.

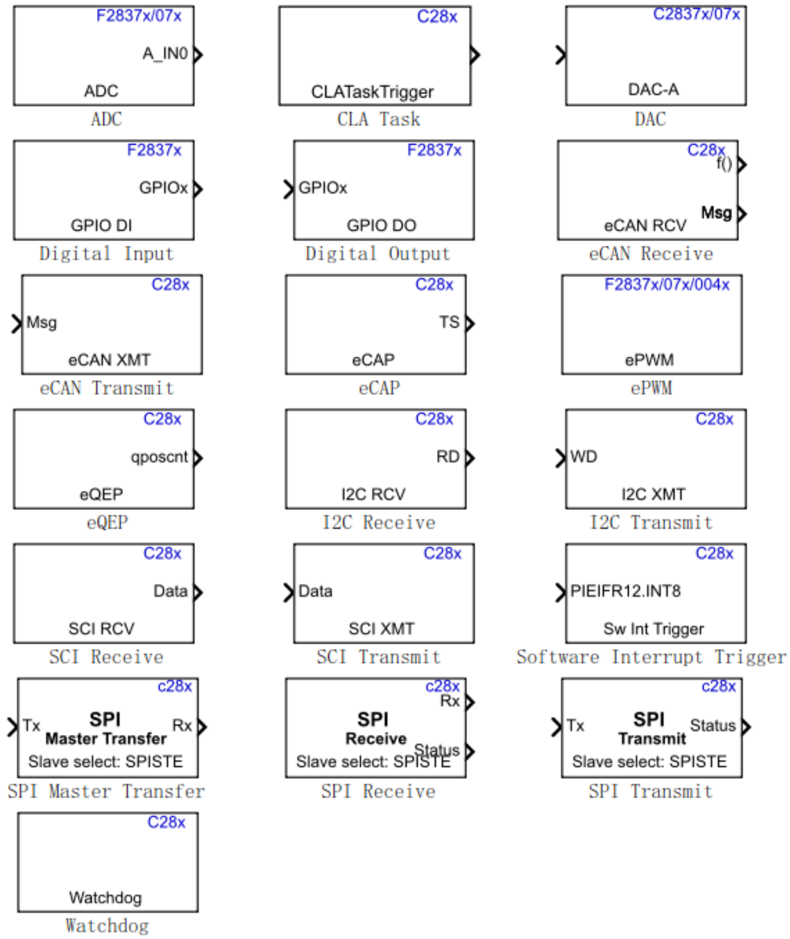


Figure 4-11 Available F2837xD blocks in Simulink

The logic design idea is introduced in Chapter 2.4 to control the operating sequence of contactors, SCRs and tap changer mechanism. The signal sequence shows in Figure 4-12. The manual signal is a command to start the tap changing event. Once the signal is received by DSP at t1, the contactor signal starts at the same time to open the contactor for preparing tap changing operation. There is a delay of time for the real contactor starts to open, because of the operating time of relay and contactor. The interval [t1, t2] is the operating time of the relay and the interval [t2, t3] is the operating time of contactor. The contactor disconnecting time interval [t1, t8] is determined by the operating time of relay and contactor, and the moving time of tap changing mechanism which is approximately

33ms. When contactor starts to open and generate a spike voltage, the voltage transducer detects a voltage drop between SCRs. The SCRs are triggered at t4 because of the triggering condition I(AB)&I(AD)&V(SCR). The interval [t5, t6] is customized in the design. T6 should start after the current is transferred from one path to the SCR path and then be cut off at zero crossing point.

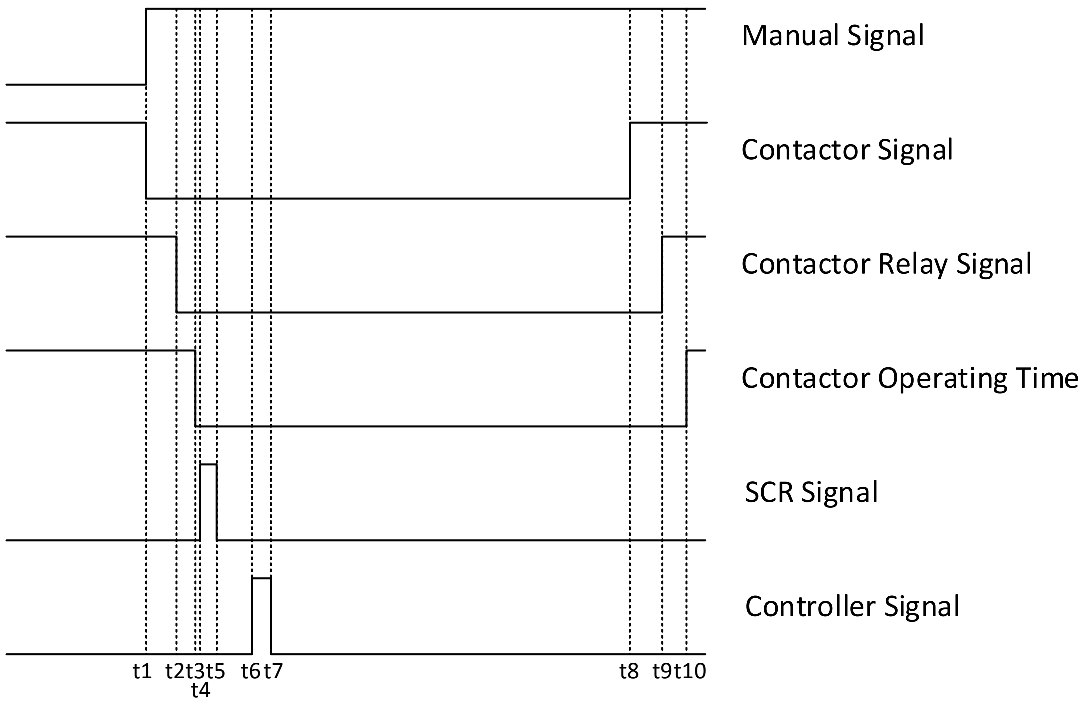


Figure 4-12 Signals sequence design

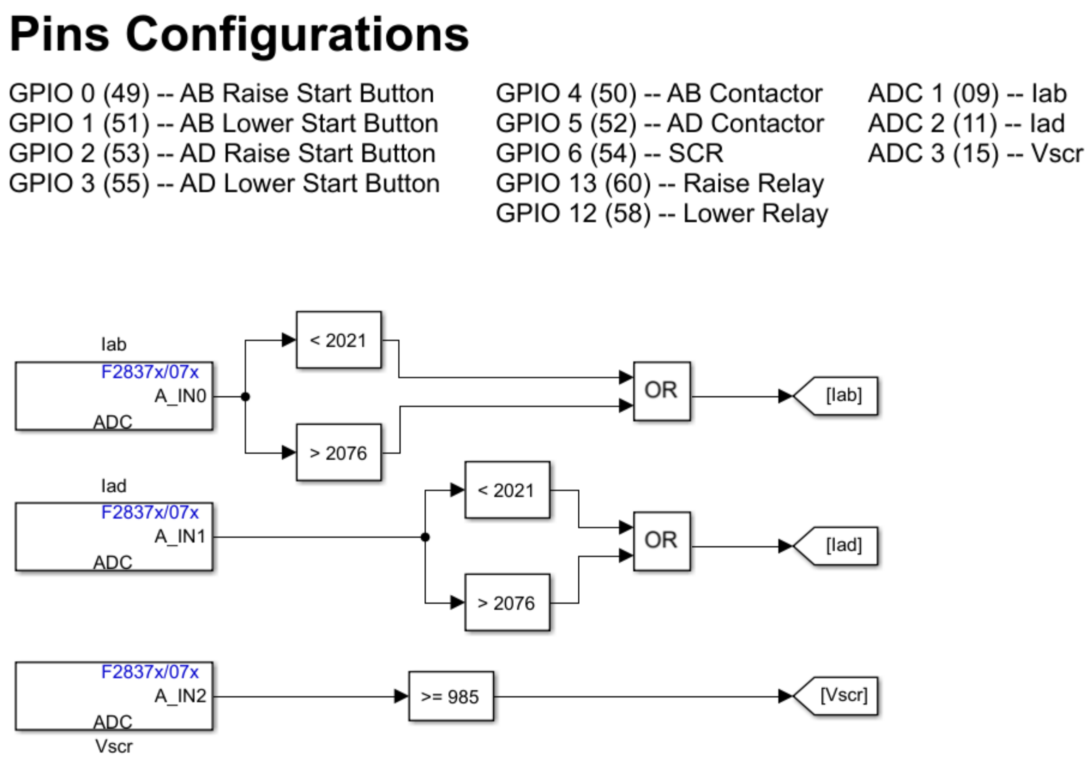
The logic design in Simulink shows in Figure 4-13. The pin configuration shows the function of each pin and the number of each pin on controlCARD for the hardware connection. The GPIO 0 to GPIO 16 can be defined as the input or output terminals. Thus, GPIO 0, GPIO 1, GPIO 2 and GPIO 3 are selected to be the manual command inputs to raise or lower the movable contacts. GPIO 4 and GPIO 5 are selected to be the terminals to control the AB and AD contactors. GPIO 6 is the gate signal to drive the anti-paralleled SCRs. GPIO12 and GPIO 13 are designed to be the output signal to raise or lower the tap changer mechanism. ADC 1, ADC 2 and ADC 3 are input pins to detect the analog signal of current AB, current AD, and SCR voltage.

Figure 4-13 (a) is the detection of a triggering condition. The range of detecting I(AB) and I(AD) depends on the accuracy of the current transducer. The triggering voltage threshold is designed to be 12 V and converted to a corresponding value 985 in a 12-bit ADC block.

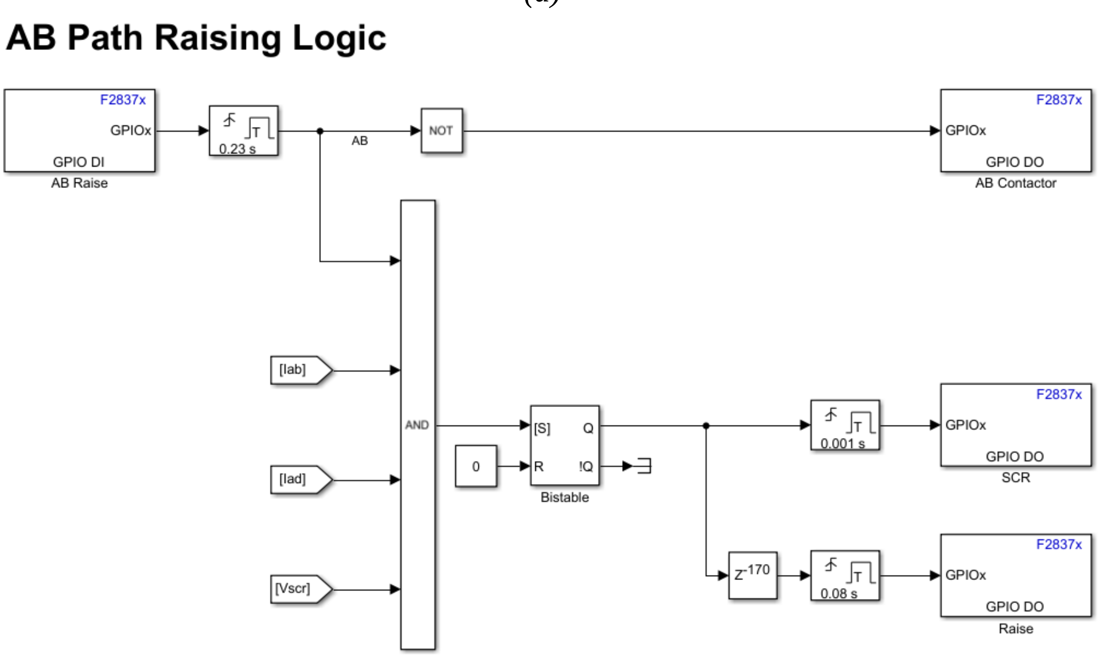
Figure 4-13 (b), (c), (d) and (e) demonstrate the four different triggering conditions, which are AB path raising, AB path lowering, AD path raising and AD path lowering. The corresponding logic chains need to be compiled into DSP before giving a command to do the tap changing operation.

Take the AB path raising for example, the SCRs logic is detected by the block diagram in Figure 14-3 (a). If the current is flowing through both AB and AD paths and the voltage drop is existing between SCRs. A signal is generated and goes through SR latch block to generate a 0.001 s signal to trigger the SCR. After the current is transferred from AB path to AD path, a 0.08 s signal is applied to the tap changer controller to move the contact in AB path raising to the adjacent tap. The total tap changing operation time is 0.23s.

This logic design is validated in the experiment and behaved very well. More details is introduced in Chapter 5.

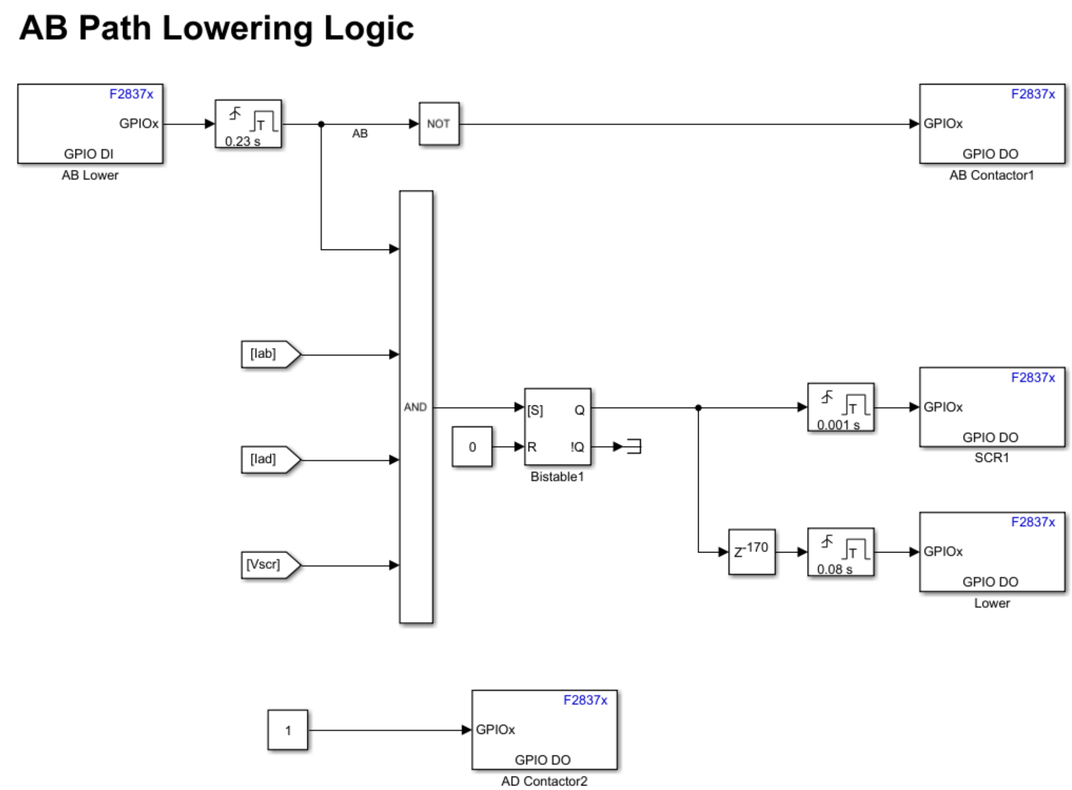


(a)

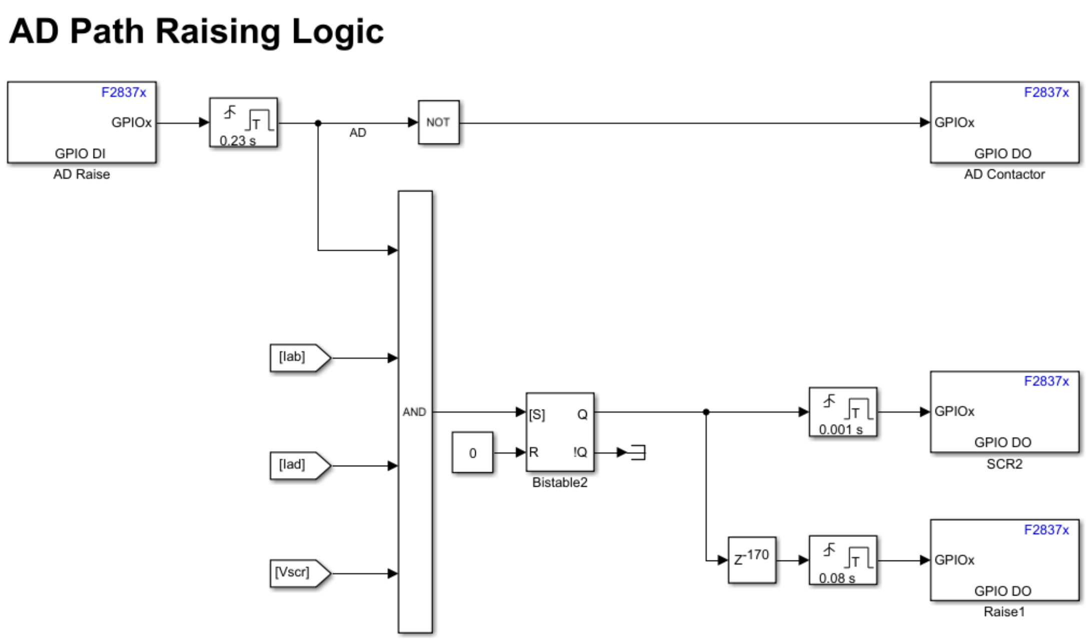


(b)

Figure 4-13 Logic design of arcless voltage regulator

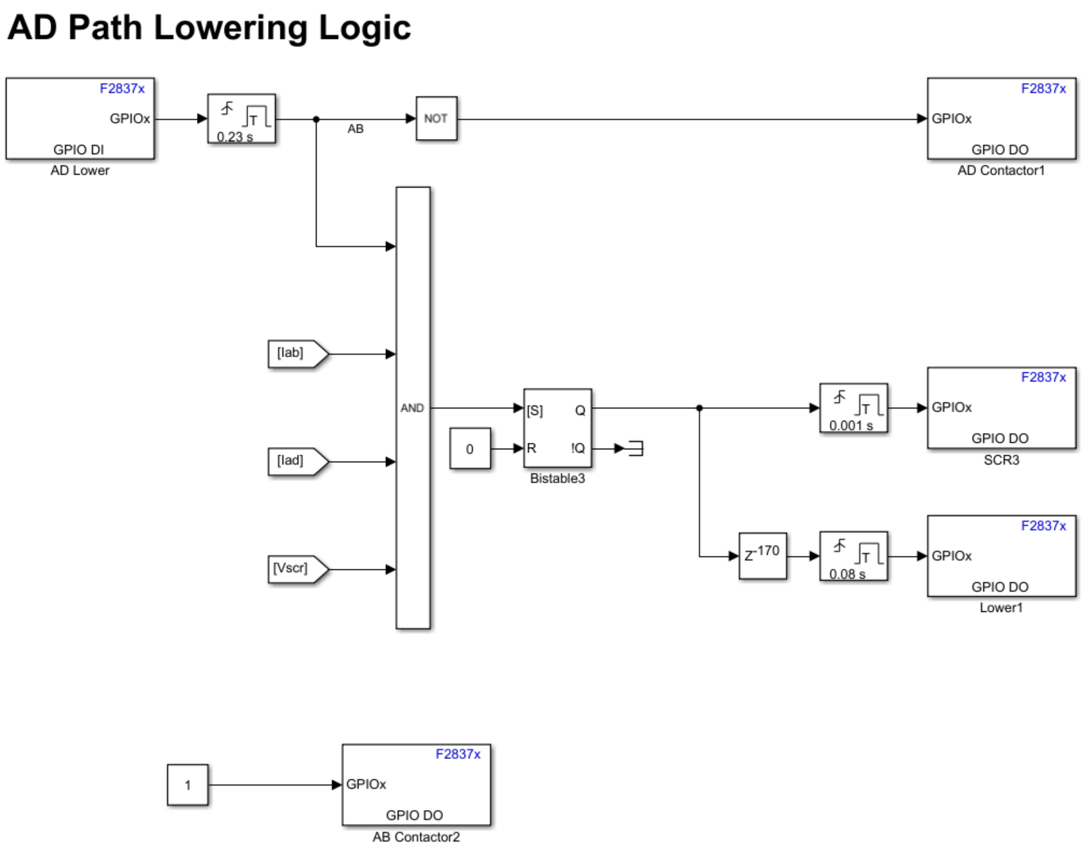


(c)



(d)

Figure 4-13 Logic design of arcless voltage regulator



(e)

Figure 4-13 Logic design of arcless voltage regulator

CHAPTER 5: EXPERIMENTAL RESULTS

5.1 Introduction

This chapter shows the experimental results according to the simulation and hardware design in previous chapters. The first experiment detects the arc in a conventional voltage regulator, while the second experiment validates the feasibility of the design arcless

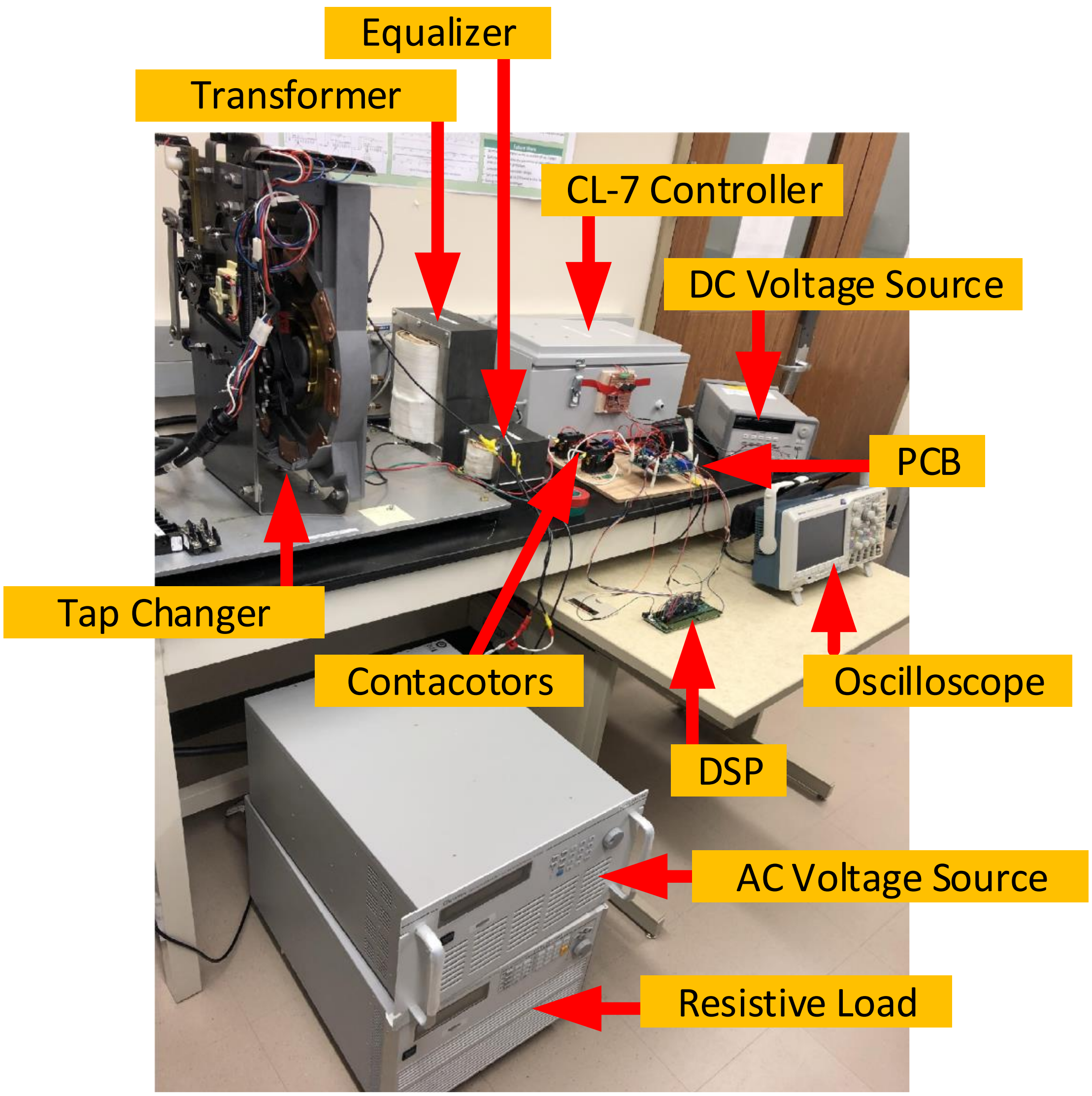


Figure 5-1 Bench setup for the experiment

voltage regulator. Section 5.2 will display the experiment bench setup and device introduction. The experiment parameters show the rated power of this experiment. Section 5.3 shows the experimental results of arcless voltage regulator and the comments on the results.

5.2 Experiment Parameter

In order to validate the feasibility of SCR based arcless tap changer, a scale down prototype shown in Fig. 5-1 is developed. The transformer is an autotransformer with the 240V AC rated input voltage in shunt winding and 96 V AC rated output voltage between each tap in the series winding. The series winding is connected with the tap changer mechanism. Two paths are extended out of the tap changer mechanism and in series with

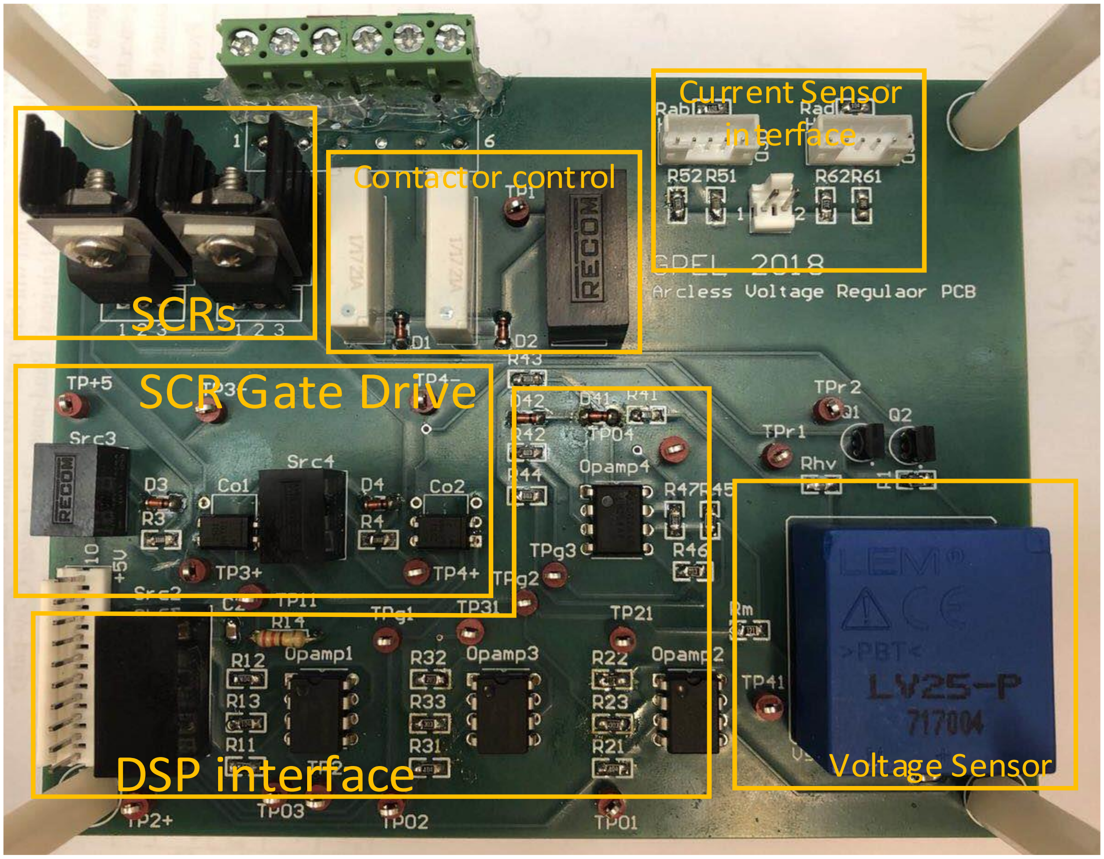


Figure 5-2 PCB design and function explanation

a contactor in each path. Then, two paths are connected together at the end side and connect with a constant current load. The DC voltage source supplies a 5V DC to PCB.

Figure 5-2 shows the finished product of PCB. All of the sections, which are be the anti-parallel SCRs and its gate drive, DSP interface, voltage sensor section and current sensor interface, introduced in Chapter 4 are integrated into PCB. The red terminals are test points for debugging the DSP and whole control loop.

The first experiment validates the appearance of arc when the tap changing event happened in the conventional voltage regulator. The load voltage is changed from 60 V to 78 V, which boosts the voltage of one step. The testing condition and components used in the prototype are listed in Table 5-1.

Table 5-1 Components parameters and testing condition of the voltage regulator

Parameters	**Symbol**	**Value**
Input Voltage	Vin	60 V
Frequency	f	60 Hz
Voltage between each tap	Vtap	24 V
Load Current	I_L	5 A

The second experiment validates the arcless procedure when the back-to-back SCRs circuit is introduced into the conventional voltage regulator. The experiment applies the operation of bridging to non-bridging position and the non-bridging to bridging position. The testing condition is listed in Table 5-2.

Table 5-2 Components parameters and testing condition of the arcless voltage regulator

Parameters	Symbol	Value
Input Voltage	Vin	60 V
Frequency	f	60 Hz
Voltage between each tap	Vtap	24 V
Load Current	I_L	12 A

5.3 Experiment Results

The first experimental results indicate the existence of arcing in the conventional voltage regulator. In Figure 5-3, the load voltage is stepped up from 60 V to 72 V. The AB path moves from one tap to the adjacent tap. The tap moving operation can be observed from the Vtap since the Vtap should change from 0 V to 24 V. The transient performance is the tap changing procedure. In this figure, the AB path current has a small ripple during the tap changing event. In other words, the arc occurs when changing the tap position. The arc voltage and arc current are shown in Figure 5-3. After the arc disappeared, the Vtap is measuring the voltage of the bias transformer and the equalizer. The Vtap becomes 24 V after the tap changing operation is completed.

In Figure 5-4, the load voltage is stepped down from 72V to 60 V. The movable contacts change from non-bridging position to bridging position. The arcing apparently occurs while one of the movable contacts is moving from one tap to another.

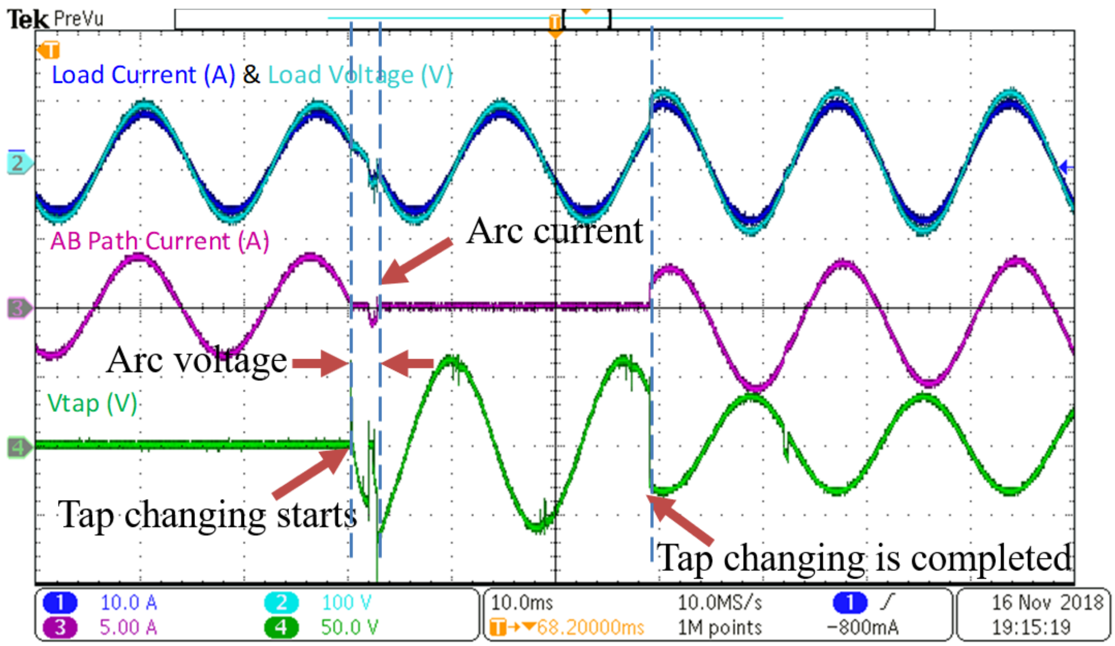


Figure 5-3 Experimental results of conventional voltage regulator

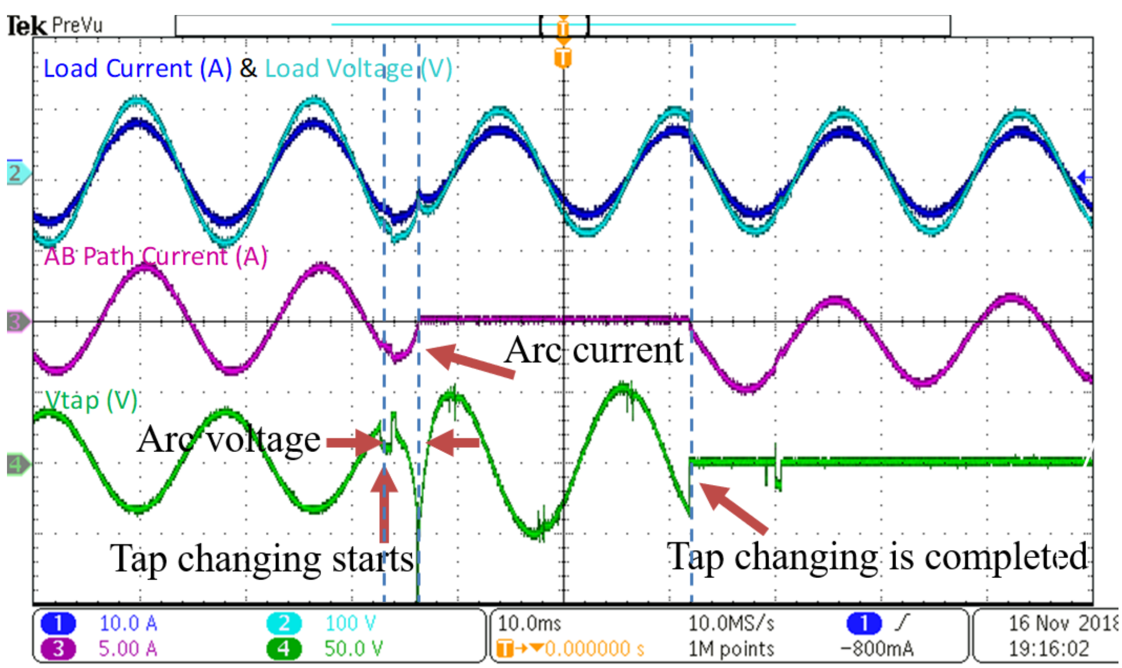


Figure 5-4 Experimental results of conventional voltage regulator

The second experiment validates the feasibility of the designed arcless voltage regulator. There are two experimental conditions testing in this experiment. One experimental condition is the movable contacts changing from non-bridging position to bridging position, while another is reversed that moving from bridging position to non-bridging position.

In Figure 5-5, the initial condition is AB and AD paths are both at the same stationary tap N, which is a non-bridging position. The command is stepping up the voltage that moves the AB path to another stationary tap. The contacts stay in a bridging position after the tap changing event.

Once the AB contactor starts to open, the SCR gate drive circuit is triggered to turn on the anti-paralleled SCRs. The current is transferred to the SCR path that depicted in Figure 5-5. Then, the SCR turns off at the first zero crossing point. The AD path current indicates that the load current flows only in AD path after turning off the SCR. The AB path current goes to zero after transferring the current to SCR path. The tap changing event happens after the AB path current decreased to 0 A. After the tap changing event, AD contactor closes again to share the load current. In Figure 5-6, the load voltage steps up to 72 V after the tap changing operation, while the current is 12 A due to the constant current load characteristics.

In Figure 5-7, the initial condition is AB and AD paths stay at adjacent taps, which is a bridging position. The command is stepping down the voltage that moves the AB path to another stationary tap. The contacts stay in a non-bridging position after the tap changing event.

The total arcless tap changing operation takes 230 ms. Though it is longer than the conventional tap changing operation time, it is better than the topology proposed in Chapter 1.5 literature review which needs 4s to complete one tap changing operation. The tap changing event without arcing can reduce the contact wear problem and reduce the frequency to replace or repair the mechanism under the oil tank. The arcless tap changing operation definitely increases the lifetime of step voltage regulator.

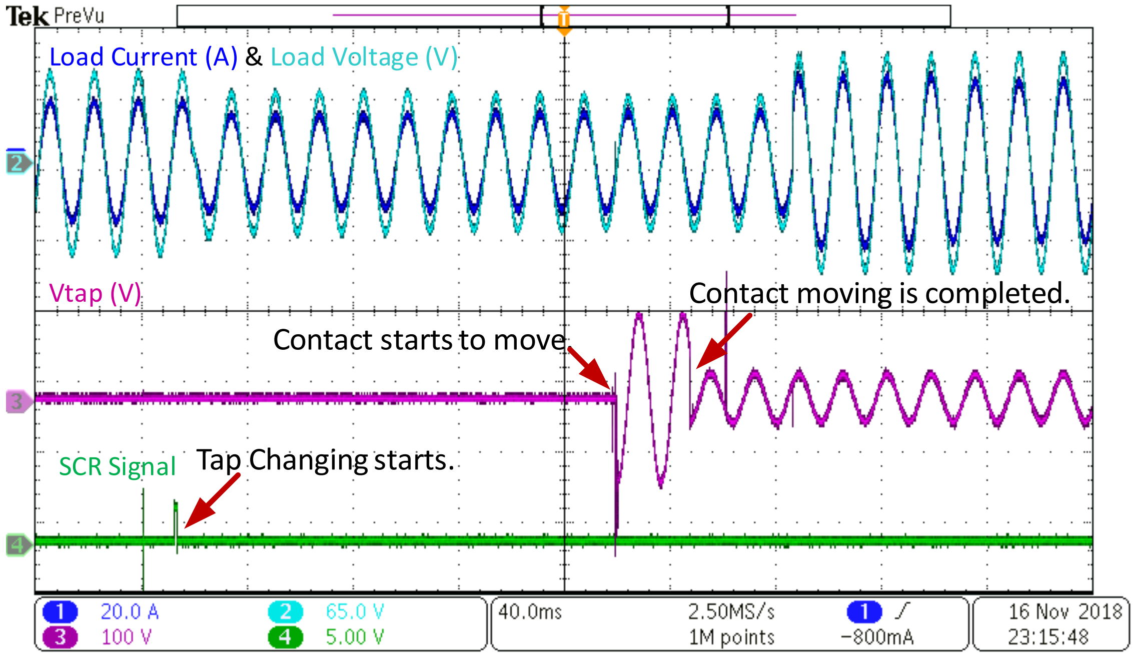


Figure 5-5 Non-bridging position to bridging position of AVR

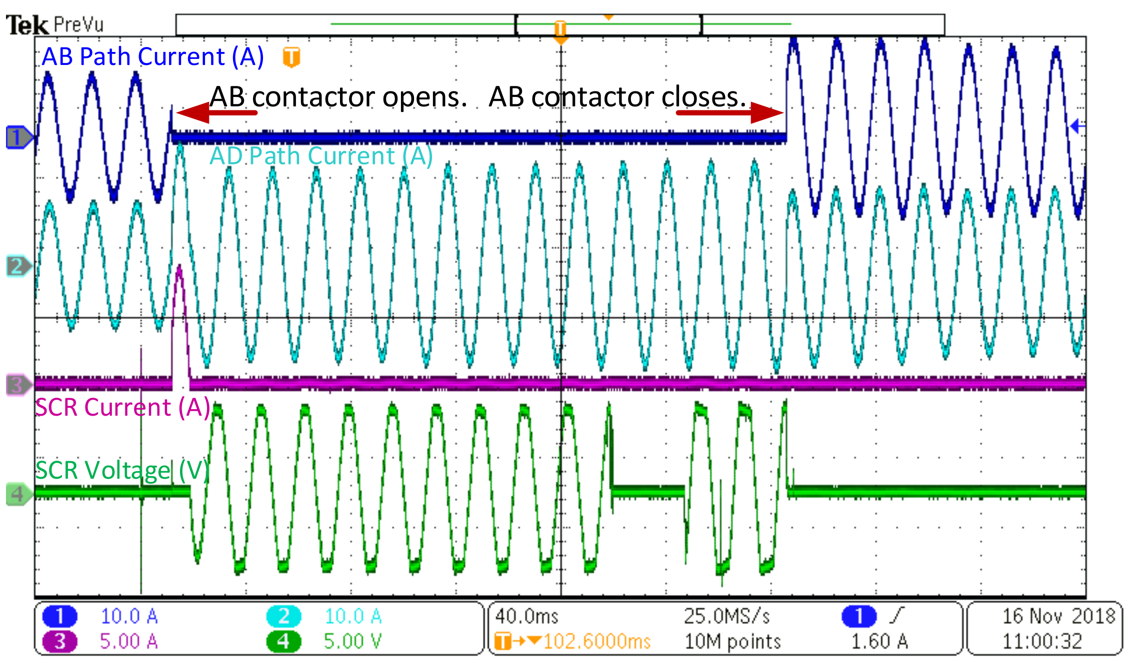


Figure 5-6 Non-bridging position to bridging position of AVR

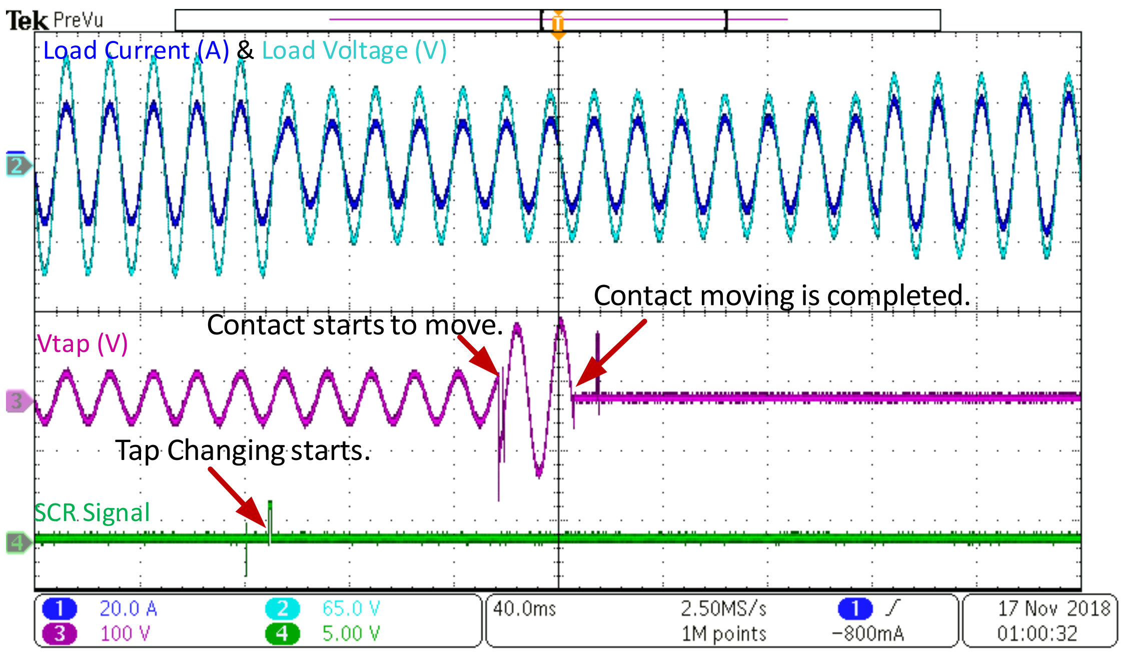


Figure 5-7 Bridging position to non-bridging position of AVR

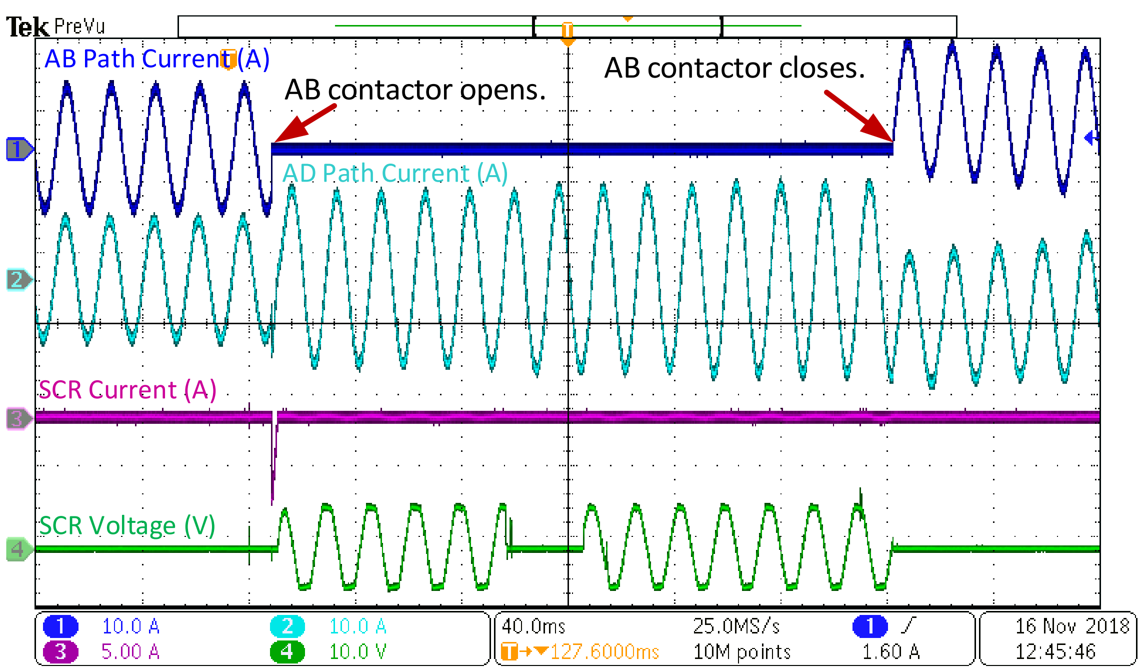


Figure 5-8 Bridging position to non-bridging position of AVR

CHAPTER 6: CONCLUSIONS AND FUTURE WORKS

6.1 Conclusion

Step type voltage regulators have used tap changing mechanisms which arc under oil during tap changes. Arcing reduces the life time and the number of electrical operations of the voltage regulators. The problem becomes more severe in today's distribution system because tap changing operations are more frequent due to distributed generations.

In the thesis, a hybrid switch based arcless voltage regulator is proposed by using a hybrid configuration of both electromechanical switch and SCRs. An SCR gating approach and control method are proposed to provide a cost-effective and reliable gate driver, so that the SCR based hybrid switch can be used for eliminating arc in voltage regulators. The simulation results and experimental results proved the feasibility of the proposed topology. The proposed method is able to eliminate the arcing during the tap changing operations, therefore increase the lifetime and the number of electrical operations of the traditional voltage regulators.

6.2 Future Work

This thesis proposed a hybrid switch based arcless voltage regulator and validates the feasibility via the experiment. But there are still a lot of potential improvements can be applied in to the design in the future. The proposed method should be applied into the conventional tap changer close loop control and be able to adjust the source voltage via step voltage regulator according to the load changing.

Thus, the future work includes but not limited to:

1) Optimize the SCRs rating via the thermal analysis of SCRs;

2) Implement IGBT based topology to eliminate the arcing and preventative autotransformer (PA) in voltage regulators;
3) Increase the rated power to validate the feasibility of this hybrid switch based arcless voltage regulator.

REFERENCES

[1] James H. Harlow, “Electric Power Transformer Engineering”, CRC Press LLC, 2004

[2] J. Faiz and B. Siahkolah, “Electronic Tap-Changer for Distribution Transformer”, Springer, June 24, 2011

[3] G. L. Quinton, “Advantages of an Arcless Voltage Regulator” in IEEE Transactions on Industry Applications, vol. 20, no. 2, pp 425-428, 1984

[4] H. A. Fohrhaltz, “Load Tap Changing with Vacuum Interrupters” in IEEE Transactions on Power Apparatus and Systems, vol. PAS-86, no. 4 pp. 422- 428, 1967

[5] U.S. Patent 7,595,614. “Load Tap Changer”, Pennsylvania Transformer Technology, Inc., Dec. 7, 2007

[6] U.S. Patent 3,195,038. “Voltage or Current Regulator Apparatus”, Breniford EiecÉric Liaised, May 4, 1962

[7] D. Dohnal, “On-Load Tap-Changers for Power Transformers”, Maschinenfabrik Reinhausen publication, Oct. 17, 2013

[8] J. G. Kassakian and T. M. Jahns, “Evolving and Emerging Applications of Power Electronics in Systems”, IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 1, no. 2, pp. 47-58, 2013

[9] U.S. Patent 3,617,862. “Arcless Load Tap-Changing Apparatus”, Allis-Chalmers, Nov. 2, 1971

[10] U.S. Patent 4,622,513, “Gating of the Thyristors in an Arcless Tap Changing Regulator”, Siemens, Nov. 11, 1986

[11] U.S. Patent 4,363,060, “Arcless Tap Changer for Voltage Regulator”, Siemens-Allis, Dec.18, 1981

[12] U.S. Patent 5,773,970, “Tap Changer with Tickler Coil for Arcless Voltage Regulator”, Maschinenfabrik Reinhausen GmbH, May.10, 1996

[13] N. Chen and L. E. Jonsson, "A new Hybrid power electronics on-load tap changer for power transformer," 2015 IEEE Applied Power Electronics Conference and Exposition (APEC), Charlotte, NC, 2015, pp. 1030-1037

[14] D. Rogers and T. Green, "An Active-Shunt Diverter for On-Load Tap Changers", IEEE Transactions on Power Delivery, vol. 28, no. 2, April 2013, pp. 649-657

[15] G. H. Cooke and K. T. Williams, "New Thyristor Assisted Diverter Switch on Load Transformer Tap Changers", IEE Proceedings, vol. 139, no. 6, November 1992, pp. 507-511

[16] J. Ainetter, G. Brauner, H. Hauer, T. Strof, A. Kalinintchenko, "Thyristor Aided Diverter Switch 'TADS'- A Progressive Concept for the Prolongation of Maintenance-Free Intervals of On-Load Tap-Changers of Transformers", International Conference on Electricity Distribution, 1999

[17] D. Gao, "A Novel Thyristor Assisted Diverter Switch for On Load Transformer Tap Changer", Transmission and Distribution Conference and Exhibition 2002, pp. 297-300

[18] R. Shuttleworth, A. Power, X. Tian, J. Jiang, B. Al Zahawi, "A Novel Thyristor-Assisted Tap-Changer Scheme", 14th International Conference and Exhibition on Electricity Distribution, pp. 28/1-28/5

[19] C. Oates, A. Barlow, V. Levi, "Tap Changer for Distributed Power", 2007 European Conference on Power Electronics and Applications, Sept. 2-5, 2007, pp. 1-9

[20] C. Keimel, G. Claydon, B. Li, J. Park, M. Valdes, "Micro-Electromechanical-Systems (MEMS) Based Switches for Power Applications", Industrial and Commercial Power Systems Technical Conference, May 2011, pp. 1-8

[21] J. H. Harlow, F. A. Stich, "An Arcless Approach to Step-Voltage Regulation", IEEE Trans. Power App. Syst., vol. PAS-101, pp. 206-2102, July 1982

[22] Croft, Terrell; Summers, Wilford, eds. (1987). American Electricians' Handbook (Eleventh ed.). New York: McGraw Hill. p. 7-124>. ISBN 0-07-013932-6

[23] M. Gerstenhaber, R. Malik, "More Value from Your Absolute Value Circuit—Difference Amplifier Enables Low-Power, High-Performance Absolute Value Circuit"

[24] User's Guide of F28379D controlCARD (TMDSCNCD28379D)