ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DESIGN AND ANALYSIS OF A SIX-PHASE VIENNA RECTIFIER

M.Sc. THESIS

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Department of Electrical Engineering

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

ALTI FAZLI VİYANA DOĞRULTUCU TASARIMI VE ANALİZİ

YÜKSEK LİSANS TEZİ

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HAZİRAN 2024

Furkan Duran, a M.Sc student of İTU Graduate School student ID 504171020 successfully defended the thesis entitled "DESIGN AND ANALYSIS OF A SIX-PHASE VIENNA RECTIFIER", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my mother, father, spouse and son...

FOREWORD

First of all, thank you for my advisor Assoc. Prof. Dr. Derya Ahmet KOCABAS to give a chance to submit this thesis, and then I would like to express my gratitude to my father and my mother for supporting me throughout my education.

The Vienna rectifier is a circuit that converts AC to DC power. It's used in many applications due to its efficiency and reliability. In telecoms, it provides stable power for equipment. Vienna rectifiers are also key components in LED drivers and battery chargers. Their ability to handle high current loads makes them ideal for these applications. In medical devices, Vienna rectifiers ensure accurate operation with low noise. They are even finding use in aircraft for converting power.

In this thesis, a six-phase Vienna rectifier is implemented, and the thermal behaviors and efficiency are compared with a three-phase Vienna rectifier at the same power level.

June 2024

Furkan DURAN
(Engineer)

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ABBREVIATIONS

AC	:	Alternating Current
CCM	:	Continuous Conduction Mode
CHT	:	Cathode heater transformer
DC	:	Direct Current
EMI	:	Electro Magnetic Interference
FCR	:	Force Commutated Rectifier
Hz	:	Hertz
IPT	:	Interphase Transformer
PT	:	Power Transformer
PWM	:	Pulse Width Modulation
SCR	:	Silicon Controlled Rectifier
TDD	:	Total Demand Distortion
THD	:	Total Harmonic Distortion
THDU	:	Total Harmonic Distortion for Voltage
TR	:	Thermal Relays

SYMBOLS

$\boldsymbol{\delta}$	:	Active Time of Vector
$\boldsymbol{\omega}$	:	Angular Frequency
$\boldsymbol{C}$	:	Capacitor
$\boldsymbol{I}$	:	Current
$\boldsymbol{D_X}$	:	Diode
$\boldsymbol{D}$	:	Duty Cycle
$\boldsymbol{f}$	:	Frequency
$\boldsymbol{i_L}$	:	Inductance Current
$\boldsymbol{L}$	:	Inductor
$\boldsymbol{k}$	:	Kilo
$\boldsymbol{R}$	:	Load Resistance
$\boldsymbol{M}$	:	Modulation Index
$\boldsymbol{N}$	:	Neutral Point
$\boldsymbol{T_S}$	:	Period
$\boldsymbol{\varphi}$	:	Phase Difference
$\boldsymbol{S_R}$	:	Phase R Space Vector
$\boldsymbol{\pi}$	:	Pi
$\boldsymbol{S}$	:	Power Transistor
$\boldsymbol{v_d}$	:	Single Phase Vienna Rectifier Half of Output Voltage
$\boldsymbol{v_s}$	:	Single Phase Vienna Rectifier Source Voltage
$\boldsymbol{c_n}$	:	Thermal Capacitance
$\boldsymbol{Z_{th}}$	:	Thermal Impedance
$\boldsymbol{d}$	:	Transistor State
$\boldsymbol{E}$	:	Voltage
$\underline{\boldsymbol{u}}$	:	Voltage
$\underline{\boldsymbol{U}}$	:	Voltage Amplitude
$\boldsymbol{W}$	:	Watt

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DESIGN AND ANALYSIS OF A SIX-PHASE VIENNA RECTIFIER

SUMMARY

The Vienna rectifier is named after the city of Vienna, Austria. The rectifier was originally developed for use in telecommunications power supplies, but it has since been adopted for a wide range of applications. The Vienna rectifier is a versatile and reliable power supply circuit that is well-suited for a variety of applications.

A Vienna rectifier is an electronic circuit used to convert an alternating current (AC) to direct current (DC). The rectifier converts the AC signal using a diode bridge and then smooths it using a capacitor. The diode bridge consists of four diodes and directs the AC signal in a single direction. This allows the signal to flow in the same direction during both the positive and negative half-periods of the signal. The rectified signal is then smoothed using a capacitor. The capacitor absorbs the signal’s ripple, creating a smoother output signal.

Telecommunications equipment requires stable and regulated DC power supplies to operate reliably. Vienna rectifiers are well-suited for this application due to their high efficiency, low noise, and ability to handle high current loads. They are often used in base stations, switching equipment, and routers to convert AC mains voltage into regulated DC voltage for telecom devices. Further, LED lighting systems are becoming increasingly popular due to their energy efficiency and long lifespan. Vienna rectifiers are a key component in LED drivers, which convert AC mains voltage into DC voltage with a regulated current for driving LED lights. Their ability to handle high current loads and generate low ripples makes them ideal for LED applications. On the other hand, UPS systems are essential for critical applications that require continuous power supply during power outages or disturbances. On the other hand, Industrial motor drives control the speed and torque of electric motors, which are widely used in manufacturing, transportation, and other industrial applications. Vienna rectifiers can be used in motor drives to convert AC mains voltage into DC voltage for driving DC motors or to rectify the AC generated by induction motors.

Medical equipment often requires stable and regulated DC power supplies to ensure accurate and reliable operation. Vienna rectifiers are well-suited for this application due to their low noise and ability to handle high current loads. They are often used in medical imaging devices, life support equipment, and other medical devices.

Battery charging systems are used to charge batteries in various applications, such as electric vehicles, power tools, and mobile devices. Vienna rectifiers can be used in battery chargers to control the charging process and regulate the charging voltage and current. Their efficiency and ability to handle high current loads make them well-suited for battery charging applications.

One of the primary applications of Vienna rectifiers is MEA, and it is the conversion of AC power from onboard generators or the aircraft's auxiliary power unit (APU) to

DC power for various electrical systems. This includes power distribution to propulsion systems, avionics, lighting, and other essential components.

In addition to power conversion, Vienna rectifiers are also being employed in the control and regulation of electric motors and motor drives used in aircraft systems. Their ability to handle high current loads and provide stable DC power is crucial for the accurate and efficient operation of these electric systems.

Increasing of the six phases systems caused demand of the six phase rectifications. Six-phase rectification is a power conversion technique that uses six alternating current (AC) sources to deliver a smoother and more stable direct current (DC) output. This technique is becoming increasingly important in modern applications where high-power density and low ripple are required.

Six-phase rectification produces a much lower ripple in the DC output compared to single-phase or three-phase rectification. This is because the six AC sources are evenly spaced in time, which helps to smooth out the AC waveform.

Six-phase rectifiers can operate at higher power densities than their single-phase or three-phase counterparts. This is because they can handle higher current loads without sacrificing ripple control.

Six-phase rectifiers produce less noise than single-phase or three-phase rectifiers. This is because they have a lower ripple frequency, which makes it more difficult for the noise to couple into sensitive electronic circuits.

In this study, a six-phase Vienna rectifier was designed, and its performance was compared to that of a three-phase Vienna rectifier. Power loss, total harmonic distortion (THD), and semiconductor temperature were analyzed through their simulation models in PLECs. Requested output voltages are 650V, 700V, 750V and 800V, and requested output currents are 4A, 8A, 12A, 16A, 20A, 24A, 28A, 32A and 36A. Configurations of these voltages and currents were run in simulation, and results were presented.

The used control method of the designed Vienna rectifiers is hysteresis control. Hysteresis control is a used control strategy employed in Vienna rectifiers for regulating the output voltage.

Consequently, the six-phase Vienna rectifier has more advantages over the three-phase Vienna rectifier. A six-phase rectifier requires fewer switching operations to achieve the same output power as a three-phase rectifier. This results in lower switching losses and, therefore, lower power loss. A six-phase rectifier produces a smoother output voltage than a three-phase rectifier. This results in lower THD of the input current, especially for high power demands. A six-phase rectifier uses a lower switching loss, and conduction loss than a three-phase rectifier. This results in lower semiconductor temperature.

ALTI FAZLI VİYANA DOĞRULTUCU TASARIMI VE ANALİZİ

ÖZET

Viyana doğrultucu, adı Avusturya'nın Viyana şehrinden alınmıştır. Doğrultucu, ilk olarak telekomünikasyon güç kaynakları için kullanılmak üzere geliştirildi, ancak o zamandan beri çok çeşitli uygulamalarda benimsenmiştir. Viyana doğrultucu, çeşitli uygulamalar için çok yönlü ve güvenilir bir güç kaynağı devresidir.

Viyana doğrultucu, alternatif akımı (AC) doğru akıma (DC) dönüştürmek için kullanılan elektronik bir devredir. Doğrultucu, AC sinyalini bir diyot köprüsü kullanarak dönüştürür ve ardından bir kapasitörü kullanarak düzeltir. Diyot köprüsü dört diyottan oluşur ve AC sinyalini tek yönlü olarak yönlendirir. Bu, sinyalin hem pozitif hem de negatif yarım periyodlarında aynı yönde akmasına izin verir. Düzleştirilmiş sinyal daha sonra bir kapasitöre kullanılarak düzeltilir. Kapasitör, sinyalin dalgalanmasını filtreler, bu da daha yumuşak bir çıkış sinyali oluşturur.

Telekomünikasyon ekipmanı, güvenilir bir şekilde çalışabilmeleri için kararlı ve düzenlenmiş DC güç kaynaklarına ihtiyaç duyar. Viyana doğrultucular, yüksek verimlilikleri, düşük gürültüleri ve yüksek akım yükleri ile başa çıkma yetenekleri nedeniyle bu uygulama için idealdir. Baz istasyonları, anahtarlama ekipmanları ve yönlendiricilerde, telekomünikasyon cihazları için AC şebeke voltajını düzenlenmiş DC voltaja dönüştürmek için kullanılırlar. Ayrıca, LED aydınlatma sistemleri enerji verimliliği ve uzun ömürleri nedeniyle giderek daha popüler hale geliyor. Viyana doğrultucular, AC şebeke voltajını LED ışıkları sürmek için düzenlenmiş DC voltajına dönüştüren LED sürücülerin önemli bir bileşeni olarak kullanılabilir. Yüksek akım yükleri ile başa çıkma ve düşük dalgalanmalar üretme yetenekleri, onları LED uygulamaları için ideal hale getirir. UPS sistemleri, kesinti veya kesinti sırasında sürekli güç kaynağı gerektiren kritik uygulamalar için gereklidir. Öte yandan, endüstriyel motor sürücüleri, elektrik motorlarının hızını ve torkunu kontrol eder ve bunlar imalat, nakliye ve diğer endüstriyel uygulamalarda yaygın olarak kullanılır. Viyana doğrultucular, DC motorları sürümek için AC şebeke voltajını DC voltaja dönüştürmek veya indüksiyon motorları tarafından üretilen AC'yi doğrultmak için motor sürücülerinde kullanılabilir.

Diğer yandan tıbbi ekipmanlar, doğru ve güvenilir çalışmayı sağlamak için genellikle kararlı ve düzenlenmiş DC güç kaynaklarına ihtiyaç duyar. Viyana doğrultucular, düşük gürültüleri ve yüksek akım yükleri ile başa çıkma yetenekleri nedeniyle bu uygulamalar için idealdir. Tıbbi görüntüleme cihazları, yaşam desteği ekipmanları ve diğer tıbbi cihazlarda yaygın olarak kullanılmaktadır.

Akü şarj sistemleri, elektrikli araçlar, el aletleri ve mobil cihazlar gibi çeşitli uygulamalarda pilleri şarj etmek için kullanılır. Viyana doğrultucular, şarj işlemini kontrol etmek ve şarj voltajını ve akımını düzenlemek için pil şarj cihazlarında

kullanılabilir. Verimlilikleri ve yüksek akım yükleri ile başa çıkma yetenekleri, onları akü şarjı uygulamaları için ideal hale getirir.

Viyana doğrultucularının bir numaralı uygulamalarından biri, MEA ve uçaklarda kullanılan yardımcı güç ünitesi (APU) veya uçak üzerindeki jeneratörlerden AC gücünün DC gücüne dönüştürülmesidir. Bu, tahrik sistemlerine, aviyoniklere, aydınlatmaya ve diğer temel bileşenlere güç dağıtımını içerir.

Güç dönüştürme dışında, Viyana doğrultucular ayrıca uçak sistemlerinde kullanılan elektrik motorlarının ve motor sürücülerinin kontrol ve düzenlenmesinde de kullanılmaktadır. Yüksek akım yükleri ile başa çıkma ve kararlı DC güç sağlama yetenekleri, bu elektrik sistemlerinin doğru ve verimli çalışması için kritik öneme sahiptir.

Ayrıca altı fazlı sistemlerin artması, altı fazlı doğrultuculara olan talebi artırdı. Altı fazlı doğrultma, yüksek güç yoğunluğu ve düşük dalgalanma gerektiren modern uygulamalarda giderek daha önemli hale gelen, altı alternatif akım (AC) kaynağı kullanan bir güç dönüştürme tekniğidir.

Altı fazlı doğrultucular, tek fazlı veya üç fazlı düzeltmeye kıyasla DC çıkışta çok daha düşük bir dalgalanma oluşturur. Bunun nedeni, altı AC kaynağın zaman içinde eşit aralıklarla yerleştirilmiş olmasıdır, bu da AC dalga formunu yumuşatmaya yardımcı olur.

Altı fazlı doğrultucular, tek fazlı veya üç fazlı muadillerine göre daha yüksek güç yoğunluklarında çalışabilir. Bunun nedeni dalgalanma kontrolünü kaybetmeden daha yüksek akım yükleri ile başa çıkabilmeleridir.

Altı fazlı doğrultucular, tek fazlı veya üç fazlı doğrultuculara göre daha az gürültü üretirler. Bunun nedeni, daha düşük bir dalgalanma frekansına sahip olmalarıdır, bu da gürültünün hassas elektronik devreleri etkilemesini daha zorlaştırır.

Bu çalışmada, altı fazlı bir Viyana doğrultucu tasarlandı ve performansı üç fazlı bir Viyana doğrultucunun performansıyla karşılaştırıldı. Güç kaybı, toplam harmonik bozulma (THD) ve yarıiletken sıcaklığı, PLECS'deki simülasyon modelleri aracılığıyla analiz edildi. Talep edilen çıkış voltajı 650V, 700V, 750V ve 800V'dir ve talep edilen çıkış akımları 4A, 8A, 12A, 16A, 20A, 24A, 28A, 32A ve 36A'dır. Bu voltajlar ve akımlar simülasyonda çalıştırıldı ve sonuçlar sunuldu.

Tasarlanan Viyana doğrultucularının kullanılan kontrol yöntemi histeresis kontrolüdür. Histeresis kontrolü, çıkış voltajını düzenlemek için Viyana doğrultucularında kullanılan bir kontrol stratejisidir.

Bu nedenle, altı fazlı Viyana doğrultucu, üç fazlı Viyana doğrultucusuna göre daha fazla avantaja sahiptir. Üç fazlı doğrultucuya göre aynı çıkış gücü elde etmek için altı fazlı doğrultucu daha az anahtarlama işlemi gerektirir ve faz başına düşen akım miktarı yüksek güçlerde azalmıştır. Bu, daha düşük anahtarlama ve iletim kayıplarına ve dolayısıyla daha düşük güç kaybına neden olur. Altı fazlı doğrultucu, üç fazlı doğrultucudan daha yumuşak bir çıkış voltajı üretir. Bu, özellikle yüksek güç talepleri için giriş akımının THDsinin daha düşük olması anlamına gelir. Altı fazlı doğrultucu, üç fazlı doğrultucudan daha düşük anahtarlama kaybı ve iletim kaybına sahiptir. Bu, daha düşük yarıiletken sıcaklığına neden olur.

1. INTRODUCTION

A rectifier is an electrical device that converts alternating current (AC) into direct current (DC). Rectifiers are used in a wide variety of applications, including power supplies, battery chargers, and motor controllers. There are many different types of rectifiers.

Rectifiers are used in a wide variety of industries. Consumer electronics, rectifiers are used in power supplies for consumer electronics devices, such as televisions, computers, and smartphones. Industrial automation, rectifiers are used in motor controllers and other industrial automation equipment. Power generation, rectifiers are used in power generation equipment, such as wind turbines and solar inverters. Electric transportation, rectifiers are used in battery chargers and motor controllers for electric vehicles and hybrid electric vehicles. Telecommunications, rectifiers are used in power supplies for telecommunications equipment, such as base stations and routers. Data centers, rectifiers are used in power supplies for data center servers and other equipment.

Diode rectifiers are passive rectification of the AC voltage, but by using semiconductor switches or combination of diodes and semiconductor switches active rectifiers can be created. Since diode and thyristor rectifiers require input currents with high total harmonic distortion (THD) from the grid, their use should be avoided. To prevent grid disruption, some new developments or improvements of existing topologies have been performed. Vienna rectifiers are one of these active rectification topologies.

The Vienna rectifier is a type of three-phase rectifier that is known for its high efficiency and power density. It is a boost-type rectifier, which means that it steps up the input voltage to a higher output voltage. Moreover, the Vienna rectifier consists of three bidirectional switches, three inductors, and two capacitors. The bidirectional switches allow current to flow in both directions, which is why the Vienna rectifier can operate in boost mode. The Vienna rectifier operates by switching the bidirectional switches in a specific sequence. This causes the inductors to store energy and the capacitors to charge. The stored energy is then released to the output, resulting in a DC output voltage that is higher than the input voltage.

The Vienna rectifier has several advantages over other types of three-phase rectifiers, including. The Vienna rectifier can achieve efficiencies of over 98% for high efficiency applications, and Vienna rectifiers can achieve high power density values. Another advantage of the Vienna rectifiers is that they can be operated in continuous conduction mode (CCM) which means that the input current is always flowing. This results in a lower input current ripple and a higher power factor. Further, reduced voltage stress on power devices is possible with Vienna rectifier. The voltage stress on the power devices in the Vienna rectifier is lower than in other types of three-phase rectifiers, which extends the lifetime of the devices.

The Vienna rectifier is used in a wide variety of applications, power supplies for high-power electronic devices, such as electric vehicles and data center servers; battery chargers for electric vehicles and hybrid electric vehicles; motor controllers for industrial and automotive applications; renewable energy systems, such as solar and wind power systems.

1.1 Literature Review

Since AC sources transfer has been started, and AC generators are used, rectifiers are designed to have DC sources.

One of them is mechanical rectifier for high voltage is published in [1] in 1922. DC rectification is performed from generators, and generator connected to transformer and phases rectified by synchronous commutators because the semiconductor technologies were not developed. This system is called direct-current-generator of mechanical rectifier. Another old rectifier type is mercury-arc rectifiers which are known since 1902 according to the in [2]. In this topology there is a vacuum tube, and electrons are drawn from cathode to anode when anode is positive. However, if anode is negative current is not drawn. The operation of the mercury arc rectifier is based on the phenomenon of the electric arc, where it is a good conductor in the direction of the arc burst, but not in the opposite direction, and consequently only allows the passage of unidirectional currents [3]. Figure 1.1 is symbolization of the Mercury Arc Rectifier.

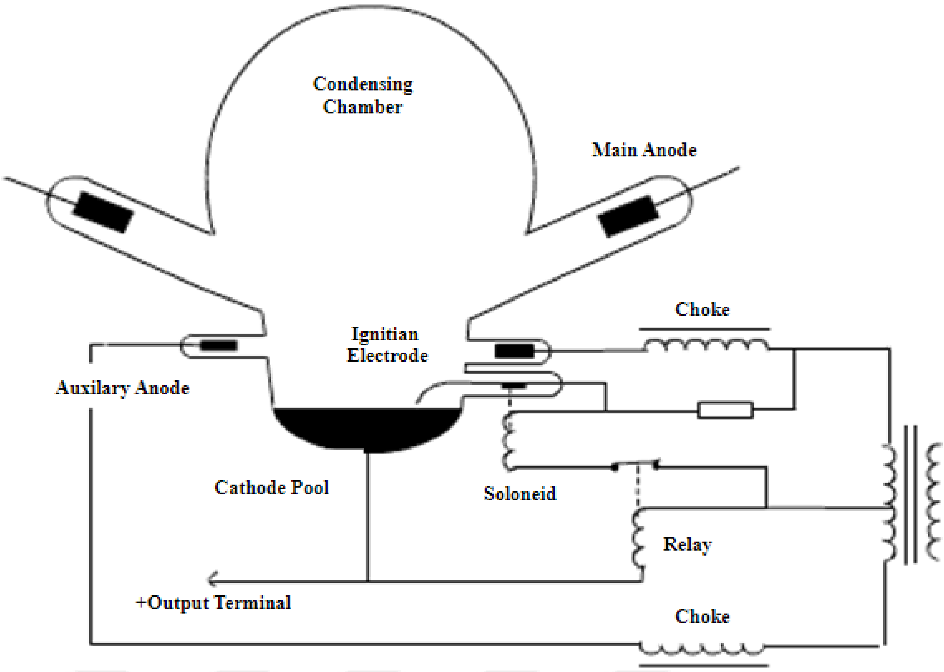


Figure 1.1: Mercury Arc Rectifier

In the forthcoming years, in [4] Clymer designed and implemented Phanotron Rectifiers to use them for elevator motors. It does not have rotating parts as mechanical rectifiers, and they are quiet in operation. They used phanotron tubes and they can work temperature between 20˚C and 80˚C. Power circuit of the rectifier is seen in Figure 1.2 and CHT is Cathode heater transformer, FG-166 is phanotron tube, IPT is interphase transformer, PT is power transformer, LA1,2,3 are anode contactors, T is thyrite arresters, and TR1,2,3 are thermal relays.

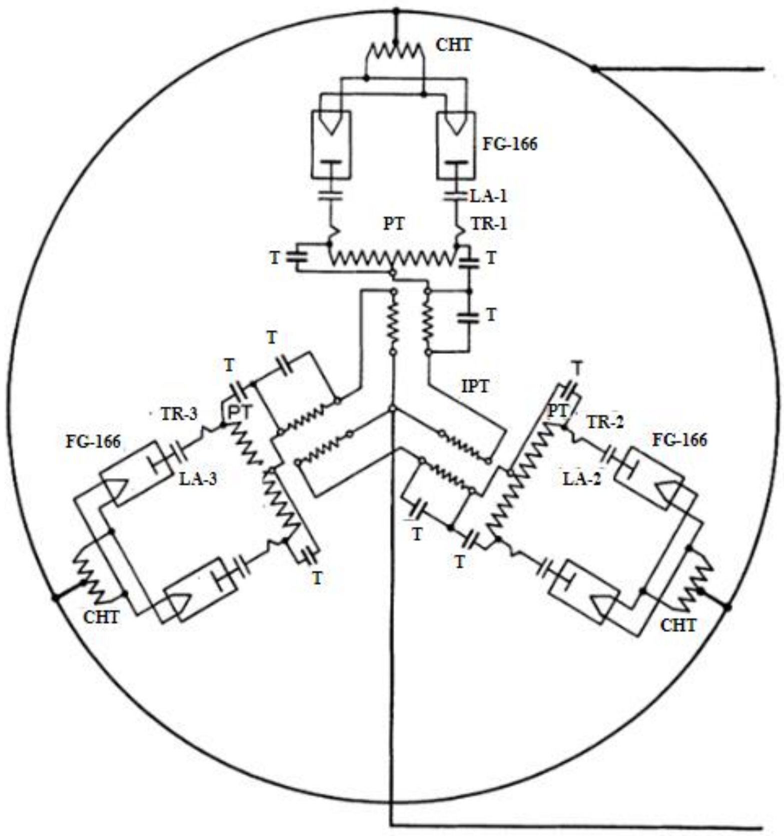


Figure 1.2: Phanotron Rectifier Power Circuit

Control of the rectifier basic is arcing of the electric inside phanotron tubes as similar to mercury arc rectifiers.

Rectifiers development was continued by using similar approaches such as mechanical rectification, and electrical arc-based solutions until the semiconductors development is achieved the proper maturity level. By controlling of the mercury arc tubes as mentioned in [5] inverting of the DC was made possible.

On the other hand, development of the diffusion techniques of silicon as explained in [6], by Smith from Bell Telephone Laboratories, lay the power diodes. Basically, having the low forward resistance, and high reverse voltage of component provided single direction current flow, and AC source have been rectified without control. Further, in 1955 Smyth from Power Sources Branch of the Squier Laboratories explained that studying of the power transistors for power conversion devices in [7]

While all investigations and development were obtained, in 1927 similar today's power electronic circuit developed in [8], but its power is low. However, the developed rectifier component production technique is similar to nowadays semiconductor production techniques. Figure 1.3 shows the used power component. In addition, by connecting the half wave rectifier as proper, full wave rectifier is also able to performed.

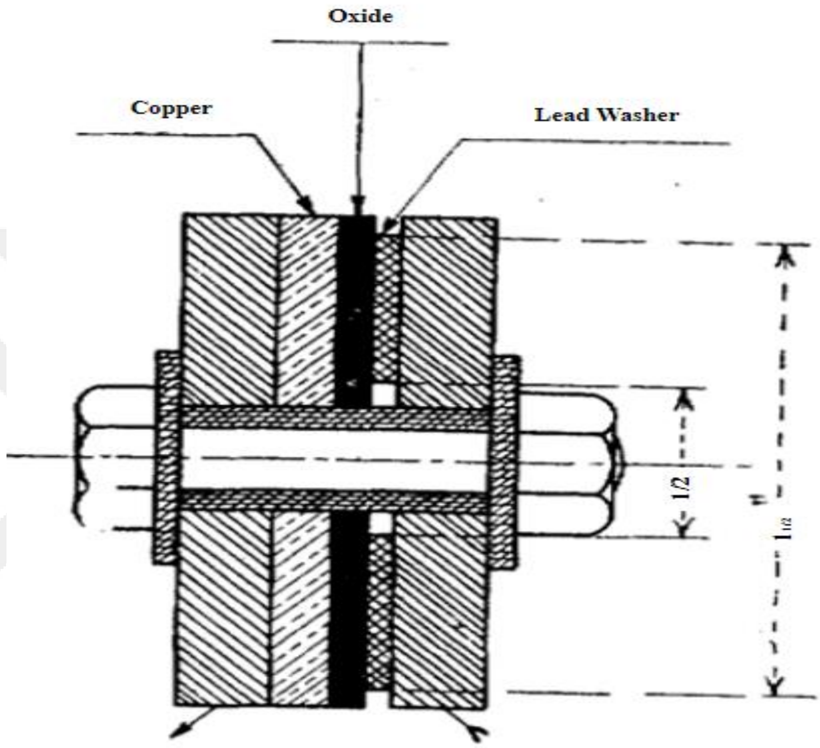


Figure 1.3: Single Half Wave Rectifier

Rectification occurs at the junction between the copper and the oxide. This activity does not cause any chemical or physical changes in the component.

Another rectification circuit technology is Germanium rectifiers. Industrial application example presented in [9]

Pfaff R presents a good example of controlled rectifiers in [10] by 1958, to control AC phase. Rectifier controls the armature current of the machine, and machine is able to controlled. Figure 1.4 shows the power circuit, and machine equivalent circuit. Thyratron 1V and 2V is controlled, and 3V and 4V are gas diode to complete the rectifier bridge circuit. Half period of voltage which is positive cycle or negative cycle provide current through 1V, and 4V or 2V and 3V according to the polarity.

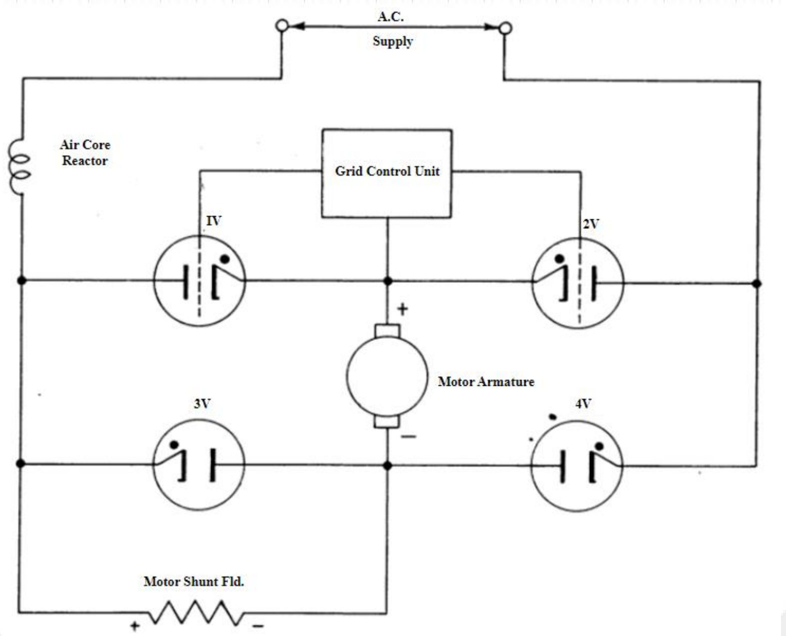


Figure 1.4: Thyratron Controlled Rectifier

By of 1956, in [11] Prince explains silicon rectifiers, and he exemplified the using of the silicon rectifier, and transistors.

In [12], many of uncontrolled current limited rectifiers such as inductance limited half wave rectifier, inductance limited full wave rectifier, capacitance limited half wave rectifier, capacitance limited voltage double, capacitance limited full wave voltage doubler, capacitance limited bridge rectifiers were explained in 1962. Using current limited rectifiers are good approach for safety critical systems to avoid exceeding of the short circuit current. For instance, inductance limited half wave rectifier is seen in Figure 1.5.

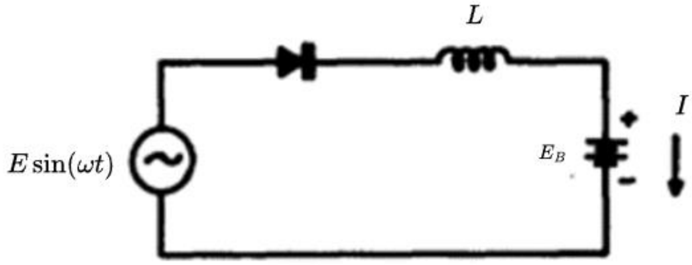


Figure 1.5: Inductance Limited Half Wave Rectifier

Output current is function of the input inductance, and maximum current has been limited according to the that dependency. The relation between input, output voltage and current is explained by

$$\frac{E_B}{E} = (0.9)\left[1 - \sqrt{\frac{\omega L I}{E}}\right] \tag{1.1}$$

where E_B is input voltage amplitude, E is output voltage, L is inductor, I is direct current, and ω is equal to $2\pi f$, f is source frequency. Other current limitation circuit details also explained in [12].

After 1960s similar approaches for controlled and uncontrolled of the power electronics circuits as nowadays are seen, because silicon-based transistors and diodes replace of the other switches components. In [13], good example of analysis the three-phase bridge rectifier is ablet to found. It explains three thyristor which means controlled semiconductor, three diode semi converter, and six thyristor converter details. Using the controlled semiconductor, thyristors, phase conduction delay is created, and output voltage was examined. It shows that 180-degree delay on phases is maximum, and current cannot draw in resistive mode. On the other hand, analysis was performed according to the load time constant.

In 1965, Distler examined single phase full-wave rectifier in [14], and filter was developed to decreasing of the output voltage ripple. This study used also silicon-controlled rectifier (SCR) as explained in [11], and added a diode to filter as seen in Figure 1.6. Thus, appeared that this diode reduced the required inductance.

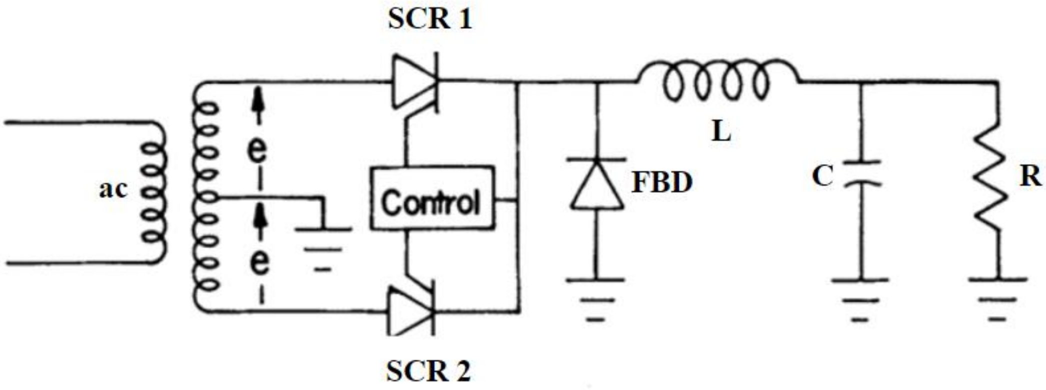


Figure 1.6: Modified Circuit

In line with all these developments, rectifiers development rapidly grow up because of silicon controlled rectifiers, in other words thyristors. Hence, analysis of the circuit, and effect analysis to source had been studied. In [15] driving of a thyristor effect on the AC power line is investigated. It explains power factor lagging. Furthermore, it investigated semi-controlled and controlled rectifiers. Duff and Ludbrook in [16] mentions about AC harmonics in AC side. Both studies showed that semi converters are not enough for high quality rectification. Additionally, in [17], some novel circuit structures are offered, and it tried increasing of the power factor of AC source. Basically, it explains inverting of the variable DC input, but the approach is same for both converting. It improved the power factor of the energy and kept stable by adding circuitry between the DC and AC.

By the next years, developing of the digital signal processing, that is used to control of the semiconductor switches, provided better solutions for rectifiers. This effect facilitates the high speed ON and OFF status change in semiconductors, and higher speed switching was made possible. Hence, rectifiers were started as PWM rectifiers as made in [18]. They might be single phase or three phase. Another important definition in [18] clarification of the phase voltages or line currents in complex domain. This transformation from three phase to complex domain which is called also as space vectors is power-invariant.

On the other hand, different control algorithm was proposed. Busse and Holtz in [19] proposed multi loop control to have unity power factor for fast switching AC to DC converters. It used complex vectors to control fast electronic switches in modulation technique which is angle modulation. The control prevented good dynamic responses but filter oscillations.

One of the interesting topologies for rectifiers is forced commutated rectifiers (FCR). They include commutating element as inductance, capacitance or diode to forcefully reduce the anode current of the silicon controlled rectifiers below the holding current value. Kolar and Zach in [20]examined and analyze different current control concepts of forced commutated rectifiers. Figure 1.7 shows the circuit of the forced commutated rectifier.

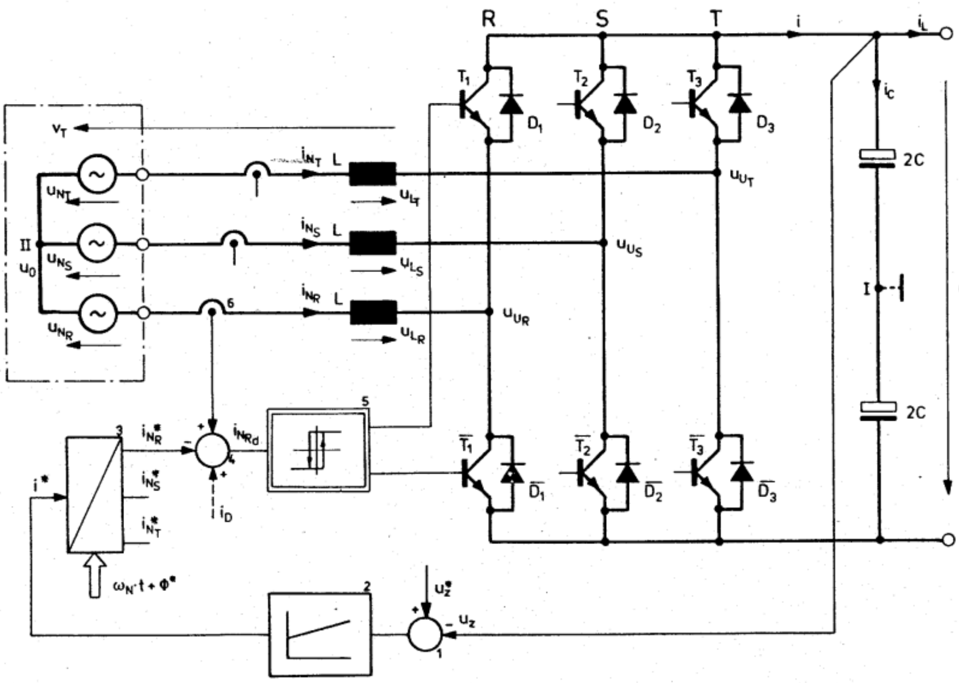


Figure 1.7: Forced Commutated Rectifiers

According to the Kolar and Zach in [20], forced commutation rectifier systems causes low influence on the mains current, and power back into mains is possible, $cos\phi$ is adjustable, DC link voltage is controlled, DC link capacitors are smaller. Furthermore, output DC voltage is bigger than the peak voltage of AC main., and it described FCR via space vectors. FCR development was not stopped, and three level boost type FCR studied in [21], in 1996. In three level DC link voltage is divided two through the capacitors, and these were balanced. Drawing current is nearly sinusoidal, and current-voltage phase difference is one.

On the other hand, different topology development was continued because of the isolation needs to have safer components in [22], 1994. A flyback converter is modified, and isolated converter system is used as three phase flyback rectifiers. Figure 1.8 shows the proposed topology. Basically, name of the topology is three phase single switch discontinuous mode rectifier.

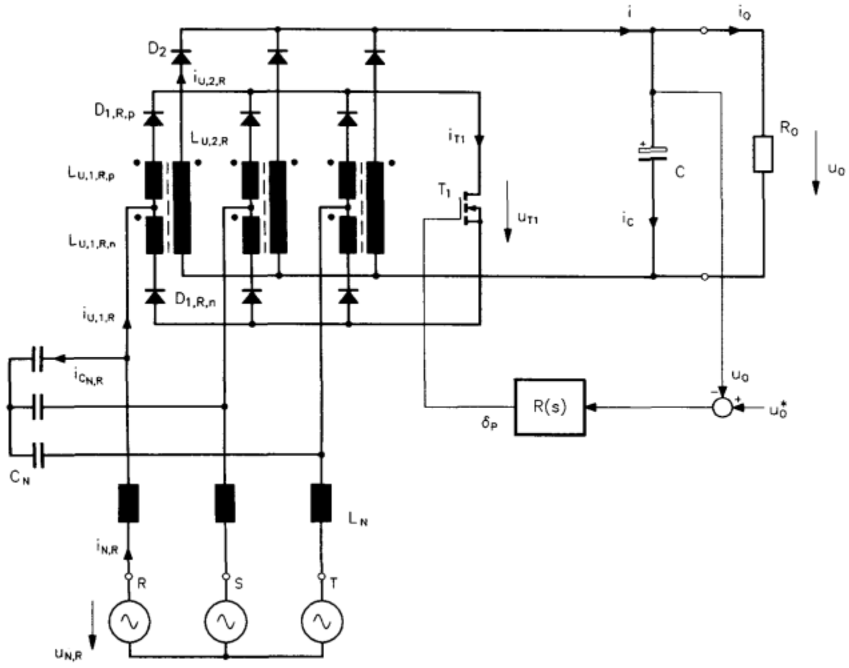


Figure 1.8: Three Phase Flyback Rectifier

Its control is simple, there is only one switch. DC output is isolated from main, and it might be used for single phase or multiple phases. It has high reliability, fault tolerance because operation is continued when one or multiple phases is failed.

Development of the rectifiers appeared limitations. Switching of transistors causes disruption in main, and IEEE 519 recommended some limitations to designed power circuits in 1992. It considers THDU level, and TDD level of circuits. That recommendation enhanced the developers' perspective, and new designs also focus power quality.

These challenges canalized the designers to have less ripple in current, less harmonic effect to main, and increasing the power factor. [23] is one of the examples this type of studies. They proposed a topology as seen in Figure 1.9.

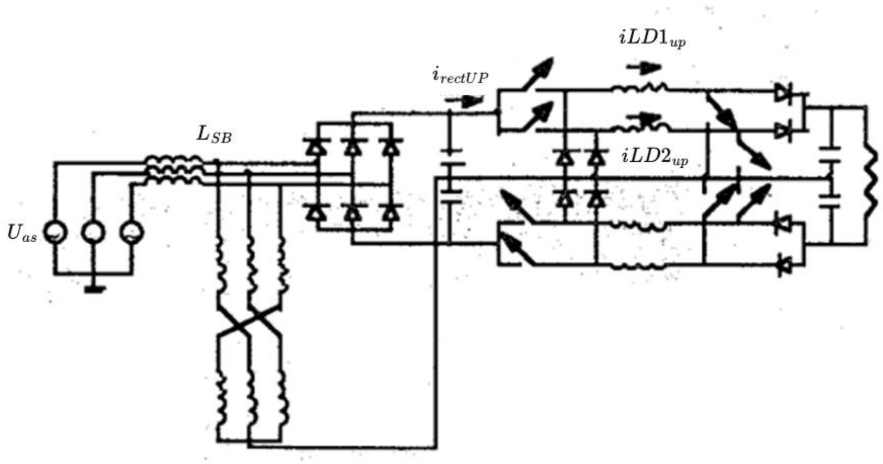


Figure 1.9: Rectifier with Interleaved DC Regulator

The topology includes zig-zag transformer, and this transformer is used to inject third harmonic current by connecting to the common node of the nodulation circuit. After rectification, there is one buck-boost converter. One inductor is used for buck or boost operation. This new topology provided large ripple cancellation in a sinusoidal input. On the other hand, according to the spice simulation, they achieve low THD results, and high power factor over wide range of input voltage.

By 1994, all consideration of the regulation, and power quality concerns caused creating new topology by Kolar, and his friends Drofenik and Zach in [24]. That topology is named as Vienna rectifier. Fundamentals of the topology is explained in Section 22VIENNA RECTIFIER. However, some details about contributing to literature are explained in this section.

Vienna Rectifier switching carrier signal is compared in [25]. The comparison was performed between non-synchronized sawtooth carrier and synchronized triangular carrier. Changing the carrier signal from sawtooth which is not synchronized, to synchronized triangular carrier caused less input current ripple by a factor of about 2 when the switching loss is not changed. That is very considerable effect to have less input EMI filter weight, size, and cost.

Another switching effect in the power electronic circuit is mode of conduction which are discontinuous and continuous mode, and in [26] analysis of the discontinues mode switching is performed. One of the effects of the clamping of phase that means discontinuous mode in time intervals provided less switching loss when it is compared to constant switching frequency that means continuous mode. On the other hand, while discontinuous mode is implemented, if modulation index is increased, third harmonic amplitude is decreased. However, to have discontinuous mode switching frequency should be higher as compared to continuous mode, and that naturally cause low ripple in current.

Chongming and Smedley in [27] proposed a different control method which is named as Unified Constant-frequency Integration, and it is basically one cycle controlling. It asserts that all three phase power factor is corrected only using one integrator, and resetting of signal through some flip-flops, comparators and logic and linear components. The method does not request multipliers. Switching frequency is constant. Hence, the proposed approach is desirable for industries. It is simple, and implementation easy.

EMI effect also is examined by developers in [28], and a circuit reconstruction was implemented. All PWM rectifiers have common mode voltage effect because of the switching that is dependent on switching frequency between main network neutral point and the central of the capacitors of the output. Proposed topology is seen in Figure 1.10.

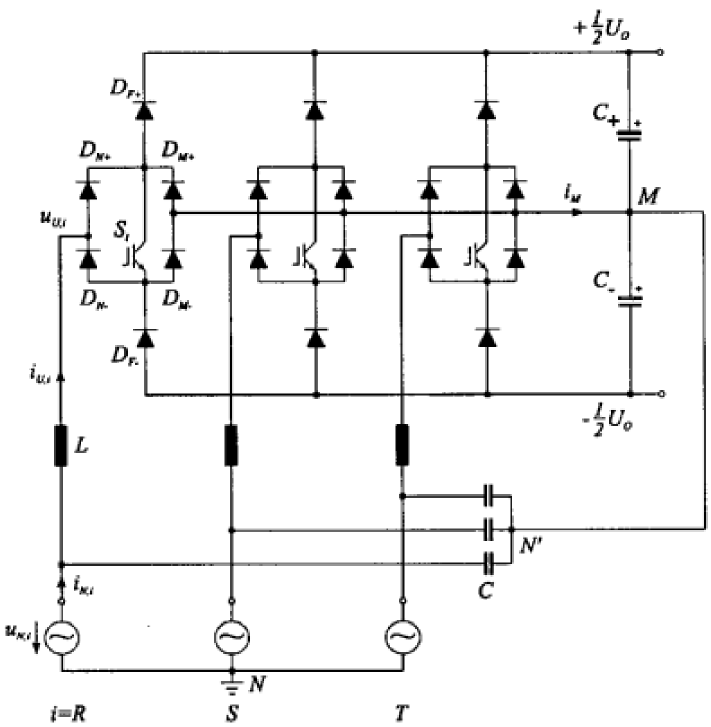


Figure 1.10: Modified Basic Structure of the Vienna Rectifier

It was reported by the proposed paper that the located of filtering capacitors C connected between DC output voltage that is the center point M and the input terminals significantly reduces the common mode EMI noise. However, it caused the increase the RMS value ripple of input current, and these result is higher copper and core losses in inductor.

Another analysis area for the Vienna Rectifier is unbalanced main input, and controlling of the unbalanced main input Vienna Rectifier, and in [29] practical realization of the current is performed. Detailed control was explained in [30].

According to the estimation in the [31], in 2003, power density of the power electronics circuit was be reached and exceeded 30kW/liter after 2015, and it was reached to 8.5kW/liter in [32], 2007. In [32], six switches Vienna Rectifier is designed, it is seen in Figure 1.11, and it includes two MOSFET to have less conduction loss. Design has much high switching frequency up to 400 kHz.

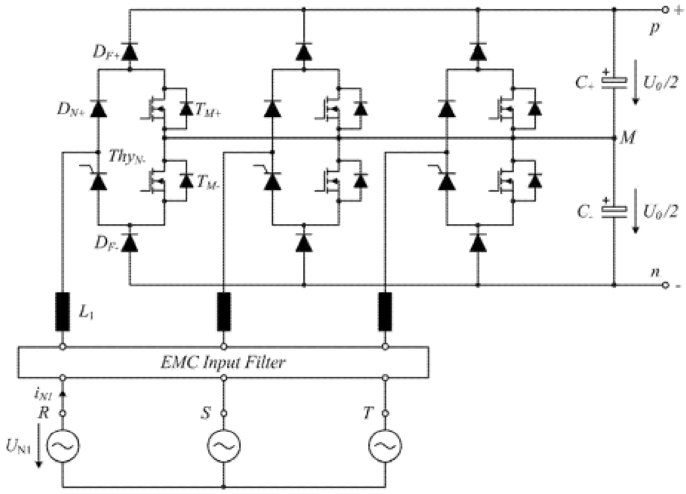


Figure 1.11: 6 Switches Vienna Rectifier

2. VIENNA RECTIFIER

Vienna rectifiers are used in certain industrial applications. They are generally designed as 3-phase. As the demand for electrical power increases, an increase in generator voltages is needed to increase the efficiency of the system. This brings about the implementation of an AC/DC converter with reduced disturbing input current effects.

Vienna Rectifier is a single direction boost type rectifier; they cannot be operated opposite direction to invert the DC source to AC. In other words, Vienna rectifiers are a nongenerative boost type rectifier [33]. It is three-level, and that topology used for active power factor correction. Its output voltage is controllable by parallel connected transistors to an uncontrolled diode in full wave rectifiers to have a kind of DCDC boost converter. They are used for different industries such as telecommunication power systems, aviation, and wind turbine systems [34], [35], [36].

Vienna Rectifiers fundamentals are acceptable as controlled output voltage by sinusoidal main current source and low-blocking voltage stress on power transistors [34]. Its output voltage is controllable by parallel connected transistors to an uncontrolled diode in full wave rectifiers to have a kind of DCDC boost converter.

Vienna rectifiers' advantages are high efficiency and power density, simple structure and high reliability [34].Especially, high reliability in safety critic systems such as aviation and automotive is hard to overcome in new electrical systems because of complexity and using of numerous components. In other words, Vienna rectifier has less active power components than that of PWM rectifiers, which is one of the main advantages.[37]. On the other hand, Vienna rectifiers' switches exposed to half of the DC bus voltage, and that makes them appropriate for high voltage DC systems [38].

Even though Vienna rectifiers are three-level converters, the controlled point is only the neutral point connection. When a phase difference exists between the reference voltage and the input current, the converter produces voltage pulses when the reference voltage and currents have different signs, leading to low-frequency voltage distortion in the power source of the rectifier [39]. Therefore, the zero crossing of each phase current affects all phases, and distortion appears especially at light loads [40] .

Vienna rectifiers are low complex, and their components have low stress. It has high power density, high efficiency, and high reliability[41].

Derivations of the Vienna rectifier discussion is started in [34]. There are possibilities to create many combinations of Vienna rectifier types according to the switch and diode placing. Mainly, three variant of Vienna rectifier existing is mentioned [42]. In that thesis these three different types of Vienna rectifiers are examined. One of them has three switches, the other two types include six switches as seen in Figure 2.1.

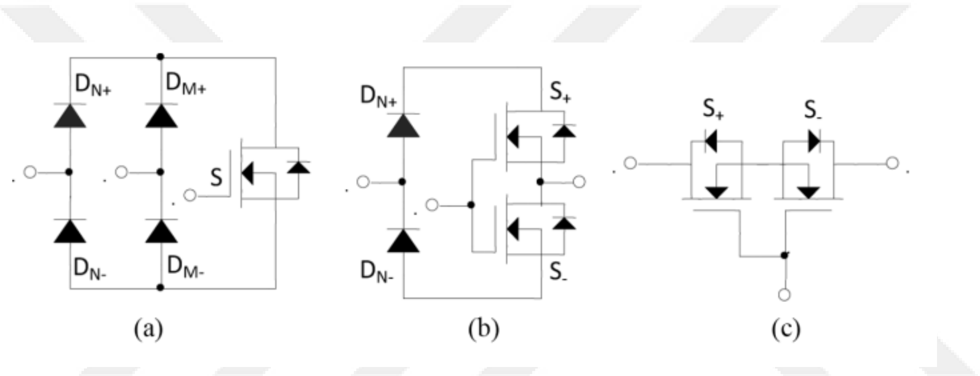


Figure 2.1 Switches Location for Different Types Vienna Rectifier

The types of the Vienna rectifier is applied according to the power level and voltage level. Different types of Vienna rectifier support the finding appropriate solutions for power volume ratio according to the requirements.

Even if there are different types of Vienna Rectifier, they have four different modes in operation. These modes are named Mode I, Mode II, Mode III and Mode IV. These modes´ combinations consists of source cycle polarity and switches ON and OFF. Obviously, four combinations emerge by multiplication of different two states, two polarities of source, ON and OFF mode switches.

2.1 Vienna Rectifier I

Vienna Rectifier-I is created by locating one switch for each phase, in other words three switches are used for one rectifier. It was designed on purpose to have less influence on the mains because of power electronic switching circuit components.

Explanation of this topology is done in [41], 1996, for academically, and it was first named Vienna Rectifier topology, however principles of the topology is prepared in [22], but it does not mention any word as Vienna Rectifier.

First examination of the topology seen in Figure 2.2, which is called in this thesis Vienna Rectifier I Topology 1, is performed in [34] by comparing another single switch Vienna rectifier. This topology includes six diode and one switch for one phase, so it named as 6D1S in [43].

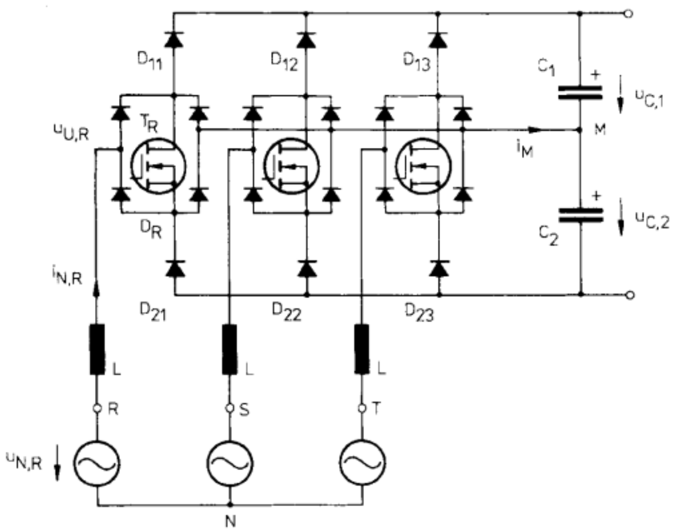


Figure 2.2: Vienna Rectifier I Topology 1

Modes effect of switching in positive source is seen in Figure 2.3. During switch is ON current flows through inductor by passing from switch to capacitors central point. In that case, inductor stores currents to work as current source when switch OFF. As seen in Figure 2.3 (a) current is passing from two different diodes. When the switch is OFF, inductor *L* discharge all current on itself. It is the same with booster mode DCDC converters. These two operations are Mode I, and Mode II. Other modes, Mode III and Mode IV are also the same which are just in negative polarity.

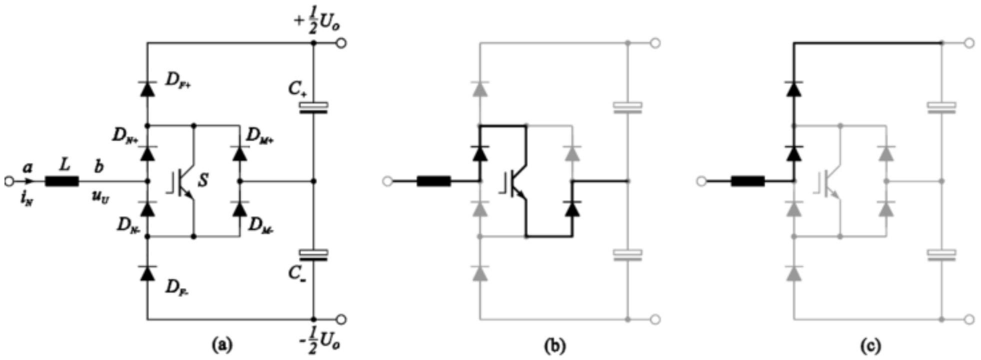


Figure 2.3: Switch ON (b) and OFF (a)

Equivalent circuit of single phase is seen in Figure 2.4.

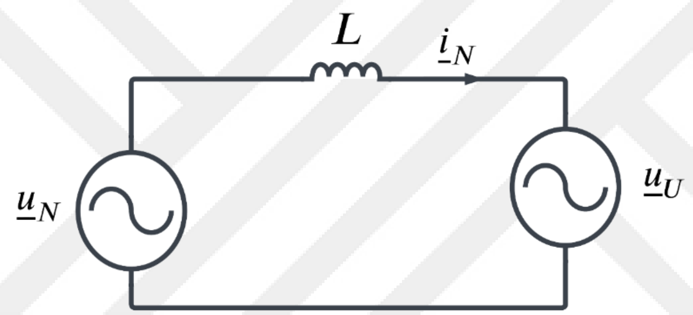


Figure 2.4: Vienna Rectifier Fundamental of AC Side for Single Phase

In analysis of the voltage according to the phasor expression for single phase modelling is

$$\underline{U}_{U,(1)} = \underline{U}_N - j\omega_N L \underline{I}_{N,(1)} \tag{2.1}$$

and current is

$$\underline{I}_{N,(1)} = \hat{I}_{N,(1)} e^{j(\varphi_N - \varphi)} \tag{2.2}$$

where φ_N is $\omega_N t$. The current of the system is defined by the voltage across the inductances connected in series on the ac side, and voltage difference consists which is

$$\underline{U}_{N,(1)} = \hat{U}_N e^{j\varphi_N} \tag{2.3}$$

because of series inductance between main voltage and rectifier input voltage fundamental $\underline{U}_{U,(1)}$. This input voltage is controlled by amplitude and phase via switching power transistors as seen in Figure 2.3.

Further, control methods implemented to Vienna Rectifier I topology, because the improve control algorithm effects to the circuits. First published control method is hysteresis control of the current in [30], and in [24] space vector modulation is implemented to detect switching operation points. Figure 2.5 shows the hysteresis control loop. It is controlled according to the output voltage through reference. Voltage error is manipulated by PI controller, it generates the current reference by multiplication of the divided multiplication voltage. Then, the current error is checked by hysteresis band limits, and switch is driven according to the generated control signal. On the other hand, capacitor balancing is considered in control loop. It is important to balance the stress on components and capacitors.

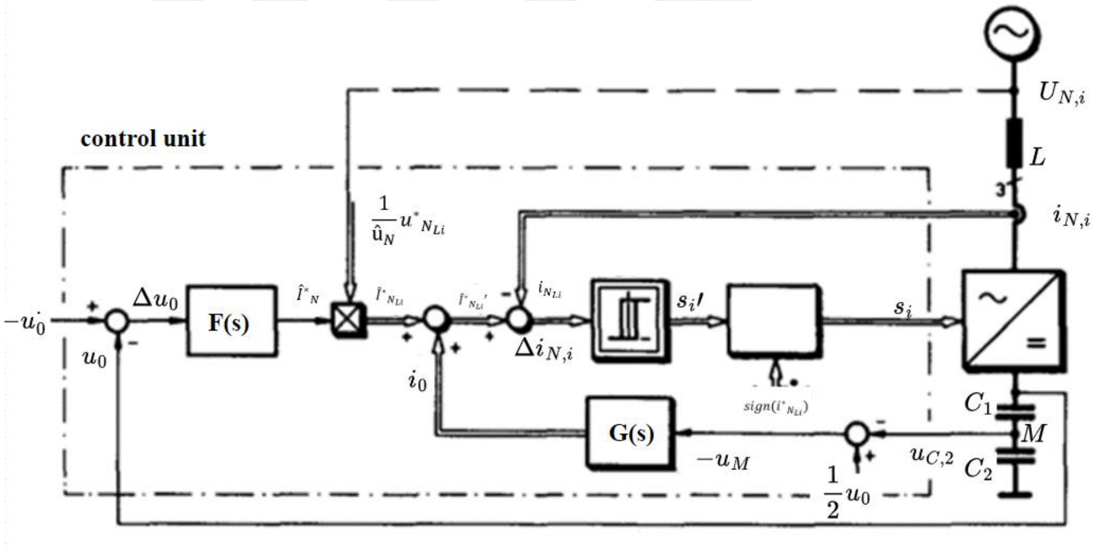


Figure 2.5: Vienna Rectifier Hysteresis Control

Another control method is using the space vectors modulation technique. When main voltage is assumed as sinusoidal and symmetric, input voltage is

$$\underline{u}_N = \hat{U}_N \, e^{j\varphi_N} \tag{2.4}$$

where

$$\varphi_N = \omega_N t \tag{2.5}$$

and ω_N is the mains angular frequency. Voltage space vector is defined as

$$\underline{u}^*{}_U = \hat{U}^*{}_U \, e^{j\varphi_N} \tag{2.6}$$

over a pulse period of switch and

$$\underline{u}^*{}_U = \hat{U}_N \, e^{j\varphi_N} - j\omega_N \underline{i}^*{}_N \tag{2.7}$$

$$\underline{i}^*{}_N = \hat{I}^*{}_N e^{j\varphi_N} \tag{2.8}$$

Space vector, $\underline{u}_U^*$ is created to generate switching states of S_R, S_S, and S_T, and it is generalized as S_i, and i is R, S, or T., and space vector is determined according to the

$$u_{U,i} = \begin{cases} sign\,\{i_N, 1\}\dfrac{U_o}{2} & if \quad s_i = 0 \\ 0 & if \quad s_i = 1 \end{cases} \tag{2.9}$$

As seen in Equation (2.9), vector is dependent on sing of the phase currents, and angular position of the space vector $\underline{i}_N$. As example, the phase angle φ_N is between $\left(-\frac{\pi}{6}, +\frac{\pi}{6}\right)$, and phase currents are $i_{N,R} > 0\,, i_{N,S} < 0\,, i_{N,T} < 0$ is shown in Figure 2.6.

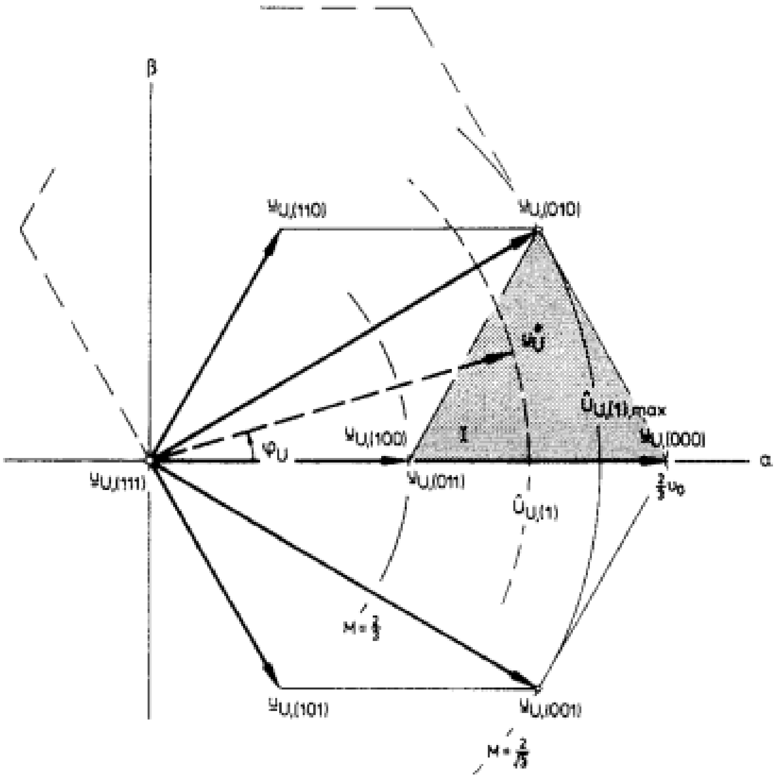


Figure 2.6: Voltage Space Vectors $\underline{\boldsymbol{u}}_{\boldsymbol{U,j}}$ ($\boldsymbol{j} = \boldsymbol{S_R}, \boldsymbol{S_S}, \boldsymbol{S_T}$)

Possible vectors to use in switching are seen as 000, 010, 011 and 100 according to the reference vector location as seen in Figure 2.6, and the reference vector is expressed as

$$\underline{u}_U^* = \delta_{(100)}\underline{u}_{U,(100)} + \delta_{(000)}\underline{u}_{U,(000)} + \delta_{(010)}\underline{u}_{U,(010)} + \delta_{(011)}\underline{u}_{U,(011)} \qquad (2.10)$$

Active time of the vectors are calculated as

$$\delta_{(000)} = \sqrt{3}Msin\left(\frac{\pi}{3} - \varphi_U\right) - 1 \qquad (2.11)$$

$$\delta_{(010)} = \sqrt{3}Msin\varphi_U \qquad (2.12)$$

and

$$\delta_{(100)} + \delta_{(011)} = 1 - \delta_{(000)} - \delta_{(010)} = 2 - \sqrt{3}Msin\left(\frac{\pi}{3} + \varphi_U\right) \qquad (2.13)$$

M is representation of the modulation index of the PWM and definition of M is

$$M = \frac{\widehat{U_{U^*}}}{\frac{1}{2}U_o} \tag{2.14}$$

and limitation of the M for reaching the overmodulation is

$$M_{max} = \frac{2}{\sqrt{3}} \tag{2.15}$$

Further, each switching sequence is chosen according to have minimum switching loss. The main purpose of the switching state change sequence is changing one switch state for each next sequence. On the other hand, for each vector in control there is redundant vectors. As explained in the example above these vectors are 100 and 011. There is not specific time distribution between them to apply.

Voltage stress of power electronics semiconductors is only half of the output voltage, and current pass via diodes and transistor are seen in Figure 2.7 [41].Vienna rectifiers have a good advantage about using components cost efficiency because half of output voltage on power electronics semiconductors On the other hand semiconductor technology limits are minor effect in high voltage demanded systems for Vienna rectifier

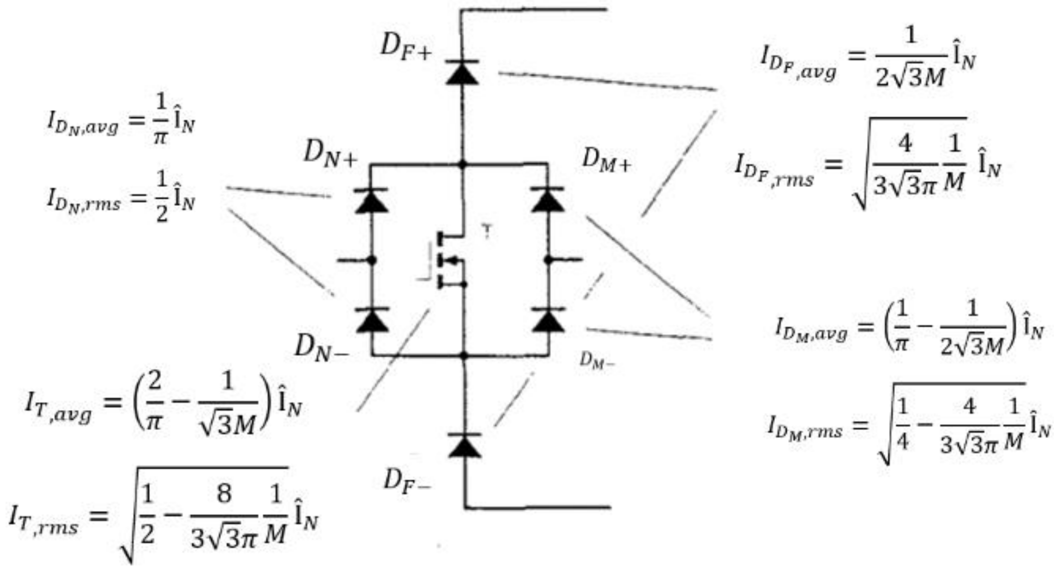


Figure 2.7: Passed Currents on Semiconductors for One Phase

2.1.1 Vienna rectifier I derivation

One of these topologies is proposed as named six switch Vienna Rectifier in [44], as seen as in Figure 2.8. It has lower conduction losses because phase current flows through the one diode when switch status is ON, and in this thesis, it is named as Vienna Rectifier I Topology 2.

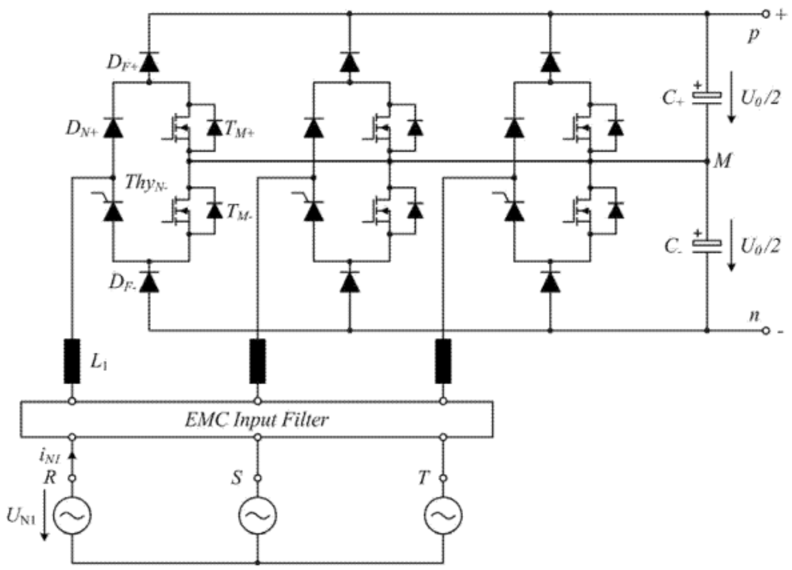
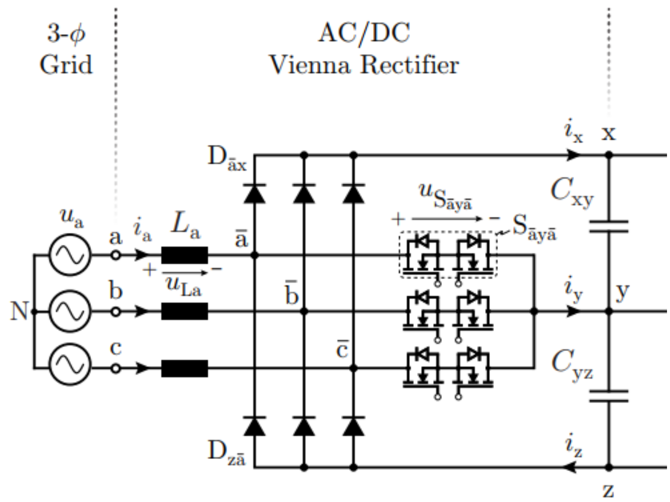


Figure 2.8: Six Switches Vienna Rectifier I Topology 2

Mainly operation modes are the same as other topologies. Inductor performs to boost the DC voltage output. During the positive cycle of main above transistor is switched, and below transistor does not need switching, or in negative main above transistor does not need switching. Hence, other transistors do not have any loss such as conduction and switching.

Another topology is obtained by connecting opposite switches from middle of the half bridge to capacitor middle point as seen in Figure 2.9, and In this thesis it is named as Vienna Rectifier I Topology 3.

During the half cycle of main (positive or negative polarity), in switching mode, one switch is operate as switching, but other switch only works in conduction mode, because in half cycle of main one switch can stop current flow, and other switches' diode direction already allows the current. If the other switch is switched that only causes switching loss, and diode conduction loss while it is OFF. Instead of that, while one switch is switched other switch is only conducted to have less loss.



(a)

Figure 2.9: Six Switches Vienna Rectifier I Topology 3

2.1.2 Comparison of the derived Vienna rectifiers I

Each topologies mentioned above have different loss because of the switching and conduction for switch, diode conduction, inductor core and winding, and output capacitor.

Power loss comparison was performed in [45] for 3 kW, 230V AC input, and 650V DC output voltage. The results of the loss according to the topologies are seen in Figure 2.10.

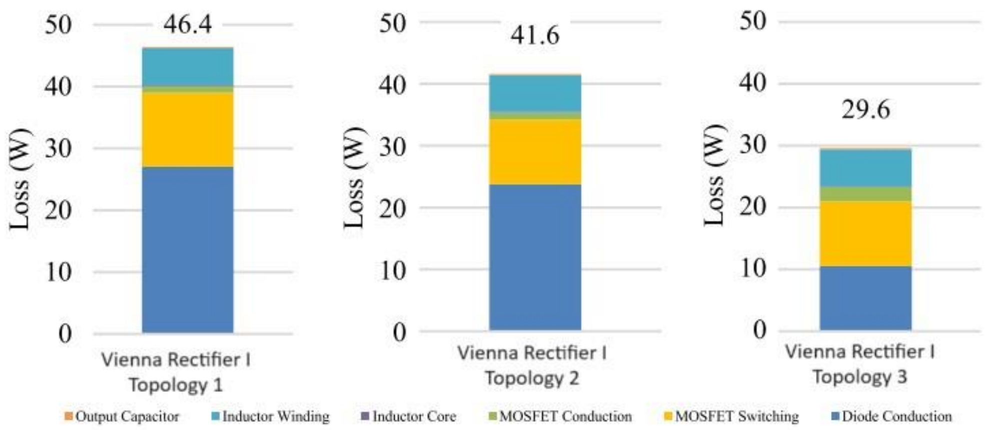


Figure 2.10: Power Loss Comparison of Vienna Rectifiers from [45]

The topology 3 has less power loss. One of the reasons is that there are only two diodes in conduction when switches are OFF state according to the comparison of the other topologies. Another one is that according to the polarity one switch is in conduction during half of the voltage source period instead of switching. It causes less power consumption when compared with passive diodes.

Another method is paralleling the switches which is known as a common method to decrease power loss. The paralleling of switches provides easy management for thermal issues, and it might increase the power density and efficiency [45]

2.2 Vienna Rectifier II

Safety critical systems might need isolated converters because of the leakage current between main and output. Vienna Rectifier II is a single-stage three-phase boost type

PWM rectifiers. Input and output are isolated. Controlling of them is possible by using of the space-vector-oriented method, and that control ensures the symmetric magnetization of the transformer [37]. They are simpler when its compared with two stage rectifiers.

As seen in Figure 2.11 Vienna rectifier has single-stage concept as mentioned above.

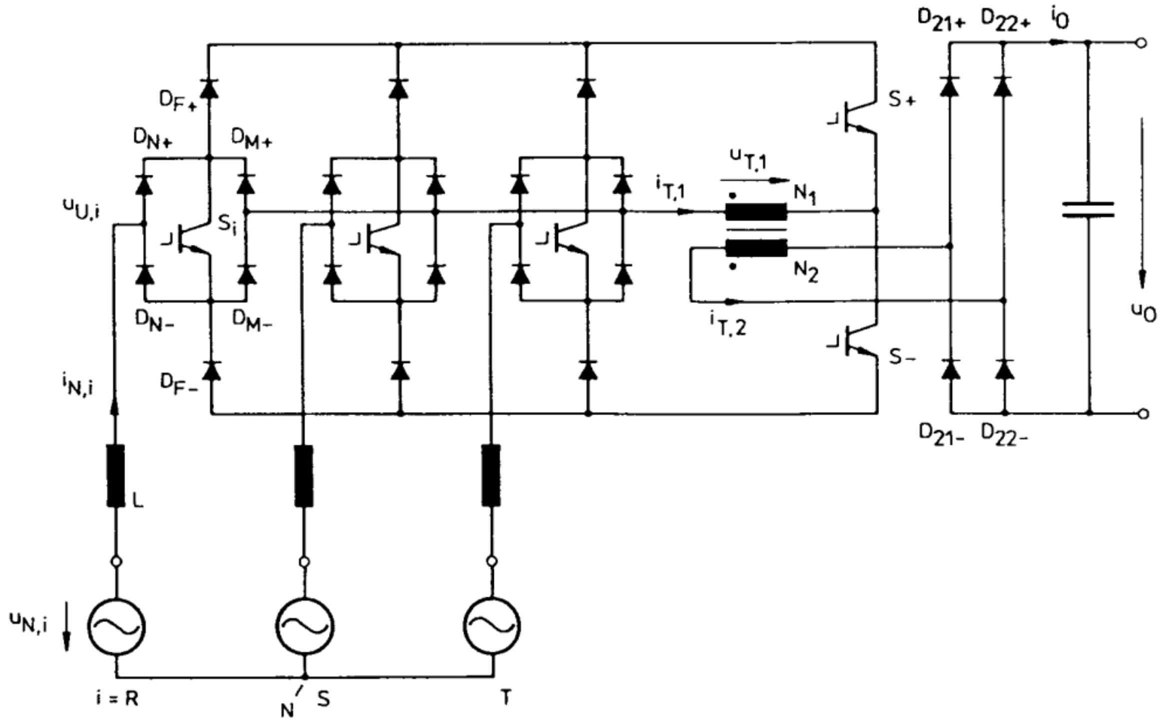


Figure 2.11: Vienna Rectifier II

Cascaded or two stage converters' each stage has its functionality. One of the tasks of the first stage is power factor correction. Sinusoidal main voltage related current is controlled, and their phase difference is tried to hold on zero. Low-frequency main current harmonics also is compatible through the transformer, and low THD [46].

Second stage tasks are handled as DCDC converter. Firstly, second stage is provided high-frequency isolation, and output voltage level is able to set through transformer and its winding ratio [46].

Vienna Rectifier II performs these functionalities as single stage rectifier.

Vienna rectifier II has some advantages as well as disadvantages. Advantages may be listed as separate optimizing of the converter stages, separate development of the input and output and buffering of failures of the between stages. However, it is complex for implementation, and it has power conversion two times. Two times power conversion may be caused low of the efficiency for system.

Operations of the Vienna Rectifier II depends on switch states which are ON or OFF, and polarity of the input phase voltage. Positive main phase current $i_{N,i} > 0$, $i = R, S, T$, flows through the $D_{F+,i}$ when the power transistor S_i is in nonconductive mode. However, when the S_i is in conductive mode, and $i_{N,i} > 0$ is positive, current flows to the transformer primary.

On the other hand, as seen in Figure 2.11, there are also $S +$ and S- switches to manage operation. Because of that reason, managing of the output voltage by generated switching state from state space vectors includes two type vectors for same length and angle vectors as seen in Figure 2.12. Vector of $S +$ is represented as + power of vector such as $(100)^{+}$, and $(011)^{-}$ for $S -$.

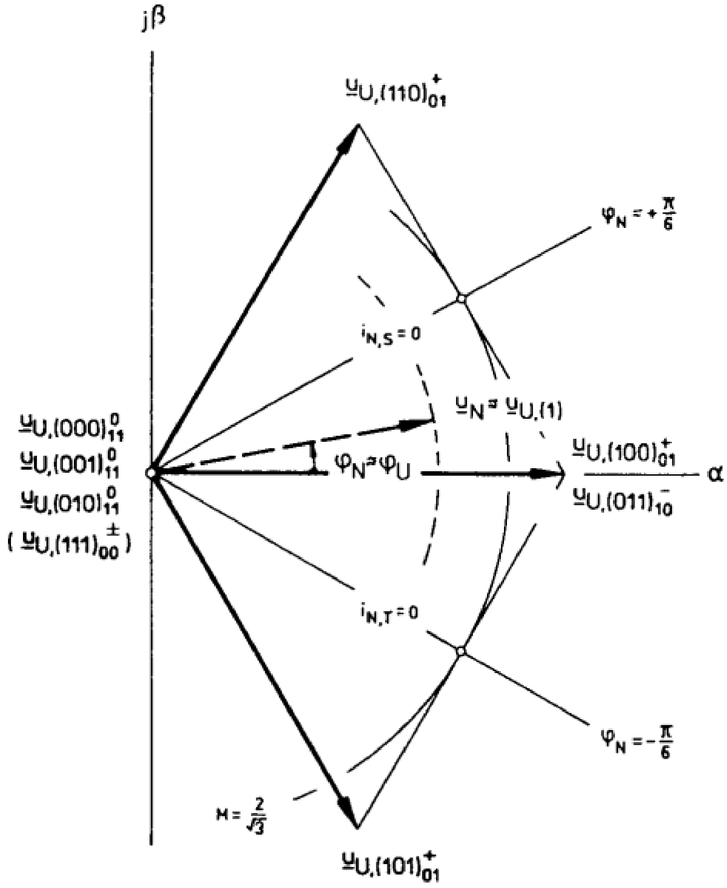


Figure 2.12: Vienna Rectifier II State Space Vector

Main purpose of the vector creation is that have guaranteed the current flow for output. Hence Table 2.1 shows the possibilities of the switching sates for all switches.

Table 2.1: Switching States of Vienna Rectifier II

S_R	S_S	S_T	s_+	s_-	$\underline{u}_{U,j}$	$sign\{u_{T,1}\}$
0	0	0	1	0	0	0
0	0	1	1	0	0	0
0	1	0	1	0	0	0
0	1	1	1	0	$\frac{2}{3}\frac{N_1}{N_2}U_o$	-
1	0	0	0	1	$\frac{2}{3}\frac{N_1}{N_2}U_o$	+
1	0	1	0	1	$-a\frac{2}{3}\frac{N_1}{N_2}U_o$	+
1	1	0	0	1	$-a^2\frac{2}{3}\frac{N_1}{N_2}U_o$	+
1	1	1	0	1	0	+/-

2.3 Vienna Rectifier III

Vienna Rectifier III is presented in [47], and its representation is seen in Figure 2.13.

It is a single-stage, buck-derived rectifier, and it has a high-frequency transformer. DC output voltage is controlled. It is a power factor correction rectifier, and efficiency is high [48]. It needs lower realization effort [47].

Inductor current, output voltage and applied volt seconds to transformer are controlled and transformer is balanced by a current controller. Output voltage control bandwidth is limited because input filter frequency is low, and there is wide range variation of main inductance. This bandwidth limitations makes more appropriate the rectifier for high power demand circuits than the telecommunications systems [48].

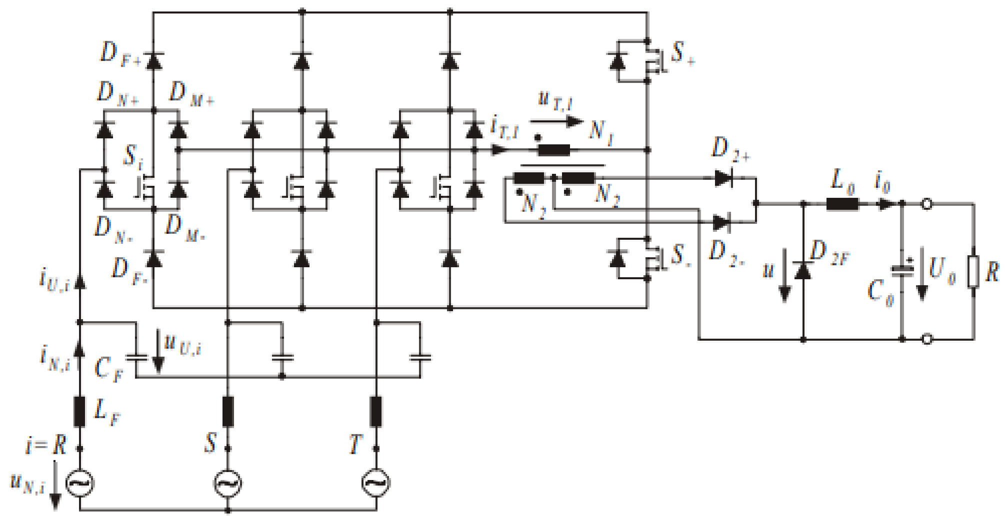


Figure 2.13: Vienna Rectifier III

Vienna Rectifier III startup does not need previous charging for output capacitor. [47]

One of the disadvantages of the rectifier Vienna Rectifier III is discontinuity of the input current. It makes necessary higher filtering performance to ensure about electromagnetic compatibility when it is compared with boost converters because of this discontinuity [47]. Another disadvantage is transformer magnetic core saturation possibility because they are operated high frequency voltage-fed.

Operation of the Vienna Rectifier III is not much different than the Vienna Rectifier II. State space vector modulation might be used to control circuit through the switches. Vector creations is similar as seen in Figure 2.12, because switches number, and locations in circuit is the same. Applied vectors and combination of these vectors and $S+$, and $S-$ is seen in Table 2.2. It is created to avoid short circuit.

Table 2.2: Switching States of Vienna Rectifier III

S_R	S_S	S_T	s_+	s_-	$i_{U,R}$	$i_{U,S}$	$i_{U,T}$	$i_{U,j}$	$u_{T,1}$	$sign\{u_{T,1}\}$
0	0	0	x	x	0	0	0	0	0	0
0	0	1	0	1	0	$-\frac{N_2}{N_1}I_o$	$+\frac{N_2}{N_1}I_o$	$\frac{2}{\sqrt{3}}\frac{N_2}{N_1}I_o e^{-j\frac{\pi}{2}}$	$-u_{N,ST}$	+
0	0	1	1	0	$+\frac{N_2}{N_1}I_o$	0	$+\frac{N_2}{N_1}I_o$	$\frac{2}{\sqrt{3}}\frac{N_2}{N_1}I_o e^{+j\frac{\pi}{6}}$	$-u_{N,RT}$	-
0	1	0	1	0	$+\frac{N_2}{N_1}I_o$	$-\frac{N_2}{N_1}I_o$	0	$\frac{2}{\sqrt{3}}\frac{N_2}{N_1}I_o e^{-j\frac{\pi}{6}}$	$-u_{N,RS}$	-
1	0	0	0	1	$+\frac{N_2}{N_1}I_o$	$-\frac{N_2}{N_1}I_o$	0	$\frac{2}{\sqrt{3}}\frac{N_2}{N_1}I_o e^{-j\frac{\pi}{6}}$	$+u_{N,RS}$	+

2.4 Modelling of Vienna Rectifier

Modelling of a power electronic circuit is important to understand the topology as mathematically and to develop control algorithms.

Basically, Vienna rectifier boosts the DC voltage from three phases. Connecting the midpoint of the capacitor to neutral point makes the three phases, four wire, three level rectifier decoupled to three single phase rectifiers.

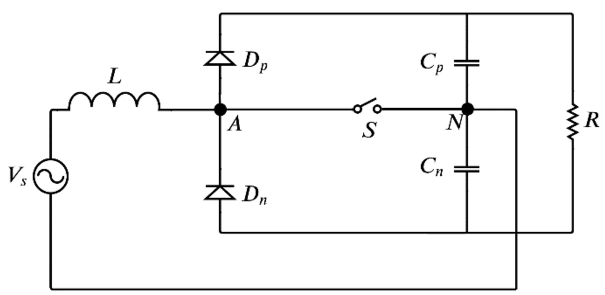


Figure 2.14: Single Phase Vienna Rectifier

Figure 2.14 **.** represents the single-phase Vienna rectifier where V_s is the input voltage, L is the input inductor. Two diodes are used to create half-bridge circuit, namely, D_p and D_n. C_p and C_n are output capacitors. The load is represented as R only, resistive load

When three phase is decomposed to three single phases, the circuit topology might be acceptable as DC-DC boost converter to model and create equations, because the uncontrolled rectified voltage is manipulated by connected switches through the inductor, and capacitor. The inductor and output capacitors are used as current, and voltage sources, respectively. When the AC voltage goes to zero, the switching duty-cycle is decreased, and output voltage is boosted to the desired value.

The average model is created according to the operation modes, and the equations are written according to those equivalent circuits in these modes.

In Mode I, there are two individual loops, and the first loop accommodates the inductance and voltage source creating the voltage equation given in (2.16) where L is the input inductor and r_L equivalent resistor of inductive L.

$$L\frac{di_L}{dt} = v_s - i_L \cdot r_L \tag{2.16}$$

The second loop accommodates the output capacitors and load resistance. By assuming the average values of capacitor voltages v_{d1} and v_{d2} are the same (v_d) , (2.17) can be written.

$$C\frac{dv_d}{dt} = \frac{-2v_d}{R} \tag{2.17}$$

In Mode II, the switch is OFF, and the equivalent equations are

$$L\frac{di_L}{dt} = v_s - v_d - i_L \cdot r_L \tag{2.18}$$

$$C\frac{dv_d}{dt} = i_L - \frac{2v_d}{R} \tag{2.19}$$

In order to combine the equivalent equations, the duty cycle of the switch (*d*) can be used representing the ON/OFF stages of the switch where d=1 and d=0 denote the switch is ON and OFF, respectively.

If the inductor and capacitor equations are merged related to switching modes (2.20) and (2.21) can be obtained.

$$L\frac{di_L}{dt} = v_s - v_d(1-d) - i_L r_L \tag{2.20}$$

$$C\frac{dv_d}{dt} = \frac{-2v_d}{R} + i_L(1-d) \tag{2.21}$$

Equation (2.20) and equation (2.21) can be expressed in state space form equation (2.22) to model a single phase Vienna rectifier.

$$\begin{bmatrix} i_L \\ \dot{v}_d \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & \frac{-(1-d)}{L} \\ \frac{(1-d)}{C} & -\frac{2}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_d \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_s \tag{2.22}$$

3. SIX PHASE VIENNA RECTIFIER DESIGN

As mentioned in Chapter 2.4six phase Vienna rectifier assumed as single-phase Vienna rectifier and system modelling and control algorithm designed according to the that assumption. The used topology is Vienna Rectifier I as mentioned above Chapter 2.1in design, and it is seen in Figure 3.1.

One phase Vienna rectifier includes one inductor as series to AC line, and two output capacitors parallel to output. These shall be calculated, and minimum values of them need to be defined in design.

Designed six phase Vienna Rectifier results will be presented as simulative, and its results will be compared with three phase Vienna rectifier for same power outputs, voltage and current.

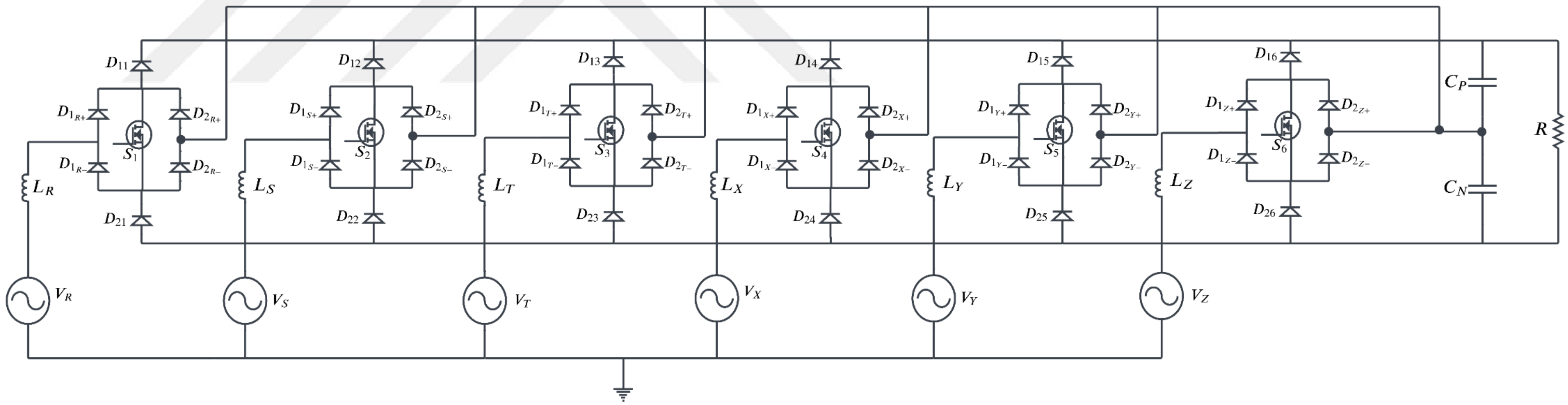


Figure 3.1 Six Phase Vienna Rectifier

3.1 Operation Modes of Single-Phase Vienna Rectifier

Connecting the midpoint of the capacitor to neutral point makes the three phases, four wire, three level rectifier decoupled to three single phase rectifiers as mentioned in Section 2.4. If converter is six phases instead of three phases assumption does not change, and single phase can be examined also for six phases modelling.

A single-phase modeled Vienna rectifier has four different operation modes. The modes are combinations of Switch ON/OFF modes, and AC polarity POSITIVE/NEGATIVE stages which can be seen in Figure 3.2.

Mode I

Mode I is represented in Figure 3.2.a when AC source in positive half-cycle, and the switch is ON state. Inductance L charges by AC source, and load R supplied through capacitors C_p and C_n. Current i_a flows from source to capacitors neutral point through switch.

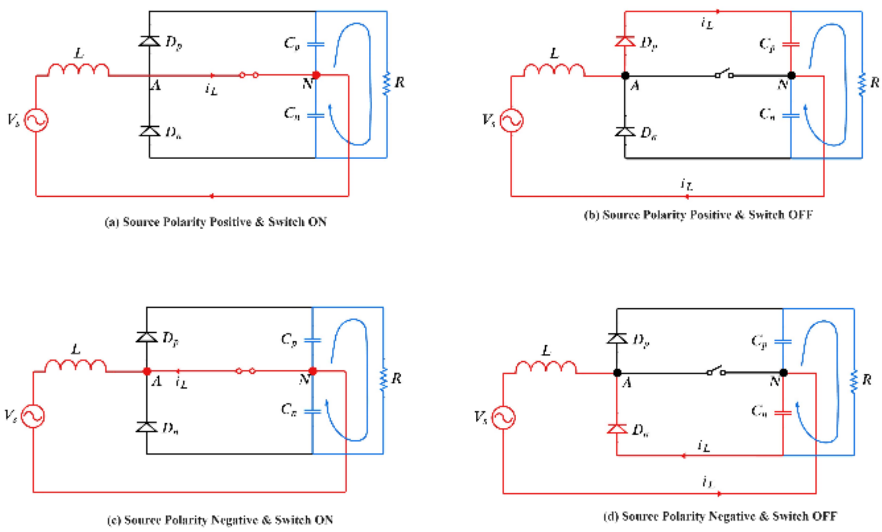


Figure 3.2: Vienna Rectifier Operation Modes

a) Source Polarity Positive & Switch ON b) Source Polarity Positive & Switch OFF c) Source Polarity Negative & Switch ON d) Source Polarity Negative & Switch OFF

Mode II

Mode II is given in Figure 3.2.b. While this mode is active, switch is OFF, and the inductor L is discharged via the capacitor C_p, and the load R is supplied by source and C_n .The current i_a flows through the capacitor C_p and diode D_p towards the neutral point.

Mode III

Mode III is seen in Fig. 3.c and this is the opposite equivalent of Mode I, and because of this reason, the current flows through switch towards the neutral point.

Mode IV

Mode IV is seen in Fig. 3.d and this is the opposite equivalent of Mode I, and because of this reason the current flows through C_n and D_n towards neutral point

3.2 Inductor Design

Inductor current increasing and decreasing depends on the switches' status, ON and OFF, and source polarity, because in negative polarity of source increasing means less current. In other words, absolute value of current increases.

Equation (2.22) first matrices term represents the inductor current ripple, time. If merged inductor current equation is written

$$\frac{di_L}{dt} = -\frac{r}{L} i_L + \frac{v_d(1-d)}{L} - \frac{v_s}{L} \tag{3.1}$$

internal resistance of inductor, its term in equation, is neglected because of its too small value. di_L represent the Δi_{pp},, and dt represent the switching ON or OFF time. In switching OFF time d is zero and equation (3.1) is written as

$$\frac{\Delta i_{pp}}{D'\, T_s} = \frac{v_d}{L} - \frac{v_s}{L} \tag{3.2}$$

where T_s is switching time and D' is (1-DutyCycle) of switch and

$$L = \frac{D'\,T_s(v_d - v_s)}{\Delta i_{pp}} \tag{3.3}$$

As seen in equation (3.3) inductance value is dependent on output voltage, input voltage, duty cycle of the switching, and desired ripple current. Inductance can be designed according to the desired ripple.

3.2.1 Effect of the inductor to input current ripple

The inductance value plays a crucial role in determining the input current ripple in a Vienna rectifier [49], and representation of the inductance current ripple is seen in Figure 3.3. This is because the inductance acts as a low-pass filter, effectively smoothing out the pulsating current waveform from the input source [50]. With a higher inductance value, the inductor has more time to store and release energy, effectively reducing the current fluctuations [51]. Conversely, a lower inductance value restricts the inductor's ability to store and release energy, leading to more pronounced current ripple [52].

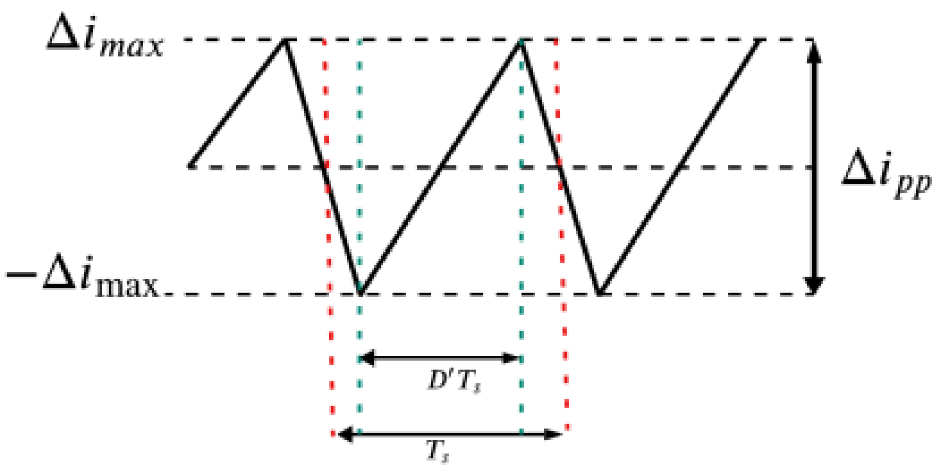


Figure 3.3: Inductance Current Ripple

The relationship between inductance and input current ripple is inversely proportional [53]. This means that as the inductance value increases, the input current ripple decreases, and vice versa [54]. This inverse relationship stems from the inherent characteristics of inductance as a filter [55]. When the input current increases, the inductor stores energy in its magnetic field [56]. Conversely, when the input current decreases, the inductor discharges this stored energy, compensating for the current fluctuations [57]. A higher inductance value enables the inductor to store more energy, enhancing its ability to smooth out the current waveform [57]

The impact of inductance on input current ripple is particularly pronounced at higher input voltage frequencies [58]. This is because the input current waveform becomes more pulsating at higher frequencies, requiring more filtering to achieve a smooth current profile [59]. A higher inductance value provides greater filtering capability, effectively suppressing current ripple at higher input voltage frequencies [60].

In summary, the choice of inductance value in a Vienna rectifier is a critical design consideration for minimizing input current ripple [60]. A higher inductance value is generally beneficial in reducing input current ripple, thereby mitigating issues such as electromagnetic interference (EMI), harmonic distortion, and reduced power conversion efficiency [61]. However, the optimal inductance value depends on various factors, including the input voltage frequency, switching frequency, load characteristics, and desired ripple level [62]. Careful consideration of these factors is essential for selecting an appropriate inductance value that ensures efficient and reliable operation of the Vienna rectifier [63].

3.3 Output Capacitor Design

Output capacitor is located to have less ripple output DC voltage. It is a filter to reduce the high frequency ripple in output.

There are two different modes for capacitors according to the switch status ON and OFF independent than the voltage polarity.

According to the equation (2.22) capacitor relation had been exposed, and to make it more meaningful the terms can be changed with different notation as made for inductor design. dV_d means voltage ripple in capacitor, and because of capacitors are parallel to output it can be accepted as output voltage. dt term represent the time difference, and that is switching frequency in our case. Thus, according to the d that represents switch state there are two different equations. When d is 1,

$$C\frac{\Delta v_d}{D.Ts} = \frac{-2v_d}{R} \tag{3.4}$$

$$C = \frac{-2v_d D.Ts}{R\Delta v_d} \tag{3.5}$$

D is duty cycle, and when d = 0

$$C\frac{\Delta v_d}{D'.Ts} = \frac{-2v_d}{R} + i_L \tag{3.6}$$

$$C = \left(\frac{-2v_d + i_L R}{R\Delta v_d}\right) D'.Ts \tag{3.7}$$

As seen in equation (3.5) and (3.7) capacitor value is dependent to demanded voltage ripple, output voltage, switching frequency, load and duty cycle of switching.

3.4 Component Selection

Inductor selection is dependent to accepted ripple and switching frequency as seen in Equation (3.3), However, the control of the designed six phase and three phase Vienna rectifier is hysteresis control, and meaning of that is switching frequency is not constant. Switching frequency of the circuit is dependent to allowed hysteresis band, on the other words allowed input current ripple. If the current ripple is high, switching frequency is low or vice versa.

The set of the hysteresis band of the input current is between 1.5A, and -1.5A, and desired inductance value is as much as keep low, and $150\mu H$ is set. In that case if the Equation (3.3) is implemented with $150\mu H$, and Δi_{pp} is 3A. Let assume the duty cycle is 0.5 and calculate the switching frequency.

$$150x10^{-6} = \frac{0.5xT_s x(400-311)}{3} \tag{3.8}$$

$$Ts = 10.11x10^{-6} \tag{3.9}$$

$$f_s = \frac{1}{T_s} \tag{3.10}$$

$$f_s = \frac{1}{10.11x10^{-6}} \tag{3.11}$$

$$f_s = 98.89\ x\ 10^3\ Hz \tag{3.12}$$

where f_s is switching frequency, T_s is switching period. As seen in Equation (3.12), switching frequency is around $98.89kHz$, because it changes according to the needed duty cycle. However, the designed control algorithm does not have switching frequency because of the hysteresis control. Although, the swiping switching frequency can be calculated by equation (3.8).

Capacitor calculation and selection have similar conditions as mentioned in inductor selection. The used equation is for capacitor calculation is Equation (3.5). Let assume that used capacitor is $2000\mu F$, because of the control method is hysteresis, and there is not constant switching frequency. Further calculated switching frequency according to the inductor selection is $98.89kHz$. In that case, voltage ripple calculation is possible and when terms are located in Equation (3.5)

$$2000x10^{-6} = \frac{800x0.5x\dfrac{1}{300x10^3}}{25\ x\ \Delta v_d} \tag{3.13}$$

$$\Delta v_d = 0.0267\ V \tag{3.14}$$

and v_d is representation of the half of the output voltage or it might be explained representation of the one capacitor value. The calculated value is already very low.

Selected semiconductor switch is SiC Mosfet from Microchip, and its produc number code is MSC035SMA070B4. Its drain source voltage is 700V, and continuous drain current in T_{case}, 25°C is $77A$. Voltages which are on MOSFETs are 400V, because of output voltage is desired as 800V. That situation is valid also for diodes.

Selected diodes is MSC050SDA070S, and its forward current is $88A$ while T_{case} temperature is 25°C.

3.5 Control Algorithm Design

The used control method is hysteresis control of the input currents. It is a simplistic and effective approach that is commonly utilized in inverters and other power electronics applications.

In a Vienna rectifier, the output voltage is generated by systematically switching power transistors on and off. The hysteresis control strategy is responsible for determining the appropriate instances to switch the transistors. Hysteresis control functions by comparing the actual current voltage to a reference current. The difference between the actual and reference currents is referred to as the error voltage. This error voltage is then utilized to regulate the switching of the transistors.

The hysteresis control strategy employs two thresholds: an upper threshold and a lower threshold. When the error voltage exceeds the upper threshold, the transistor is turned on. Conversely, when the error voltage falls below the lower threshold, the transistor is turned off.

Designed control loop algorithm is seen in Figure 3.4. u_N is representation of the input voltage, i_N is phase current, V_o is output DC voltage, V_{C_N} and V_{C_P} are capacitor voltages.

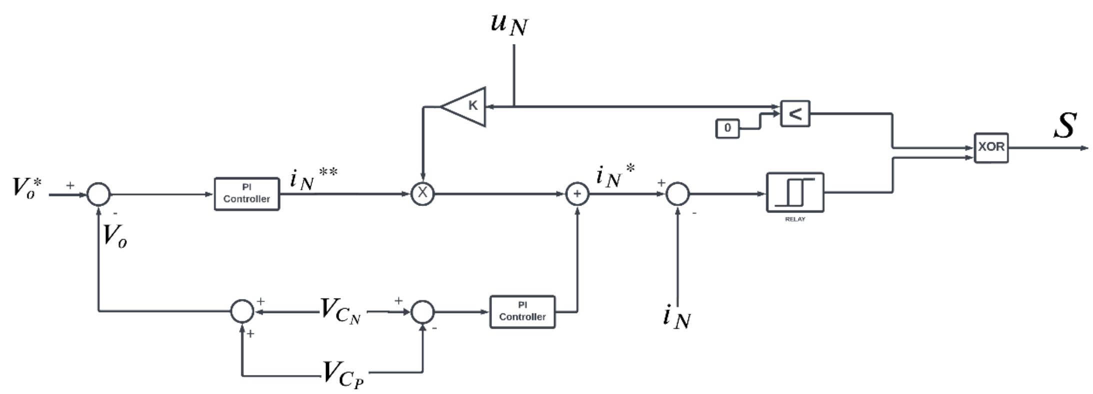


Figure 3.4: Control Loop Algorithm

PI controllers were used to create current references from voltage errors as seen in Figure 3.4. This loop is executed for each phases of the converter separately but at the same time and with same time step intervals.

4. THREE PHASE VIENNA RECTIFIER DESIGN

Design details are same as mentioned in Section 3SIX PHASE VIENNA RECTIFIER DESIGN. The used three phase Vienna rectifier topology is seen in Figure 4.1. Inductance, and capacitor values are determined with assumption which is reduced single phase of all phases.

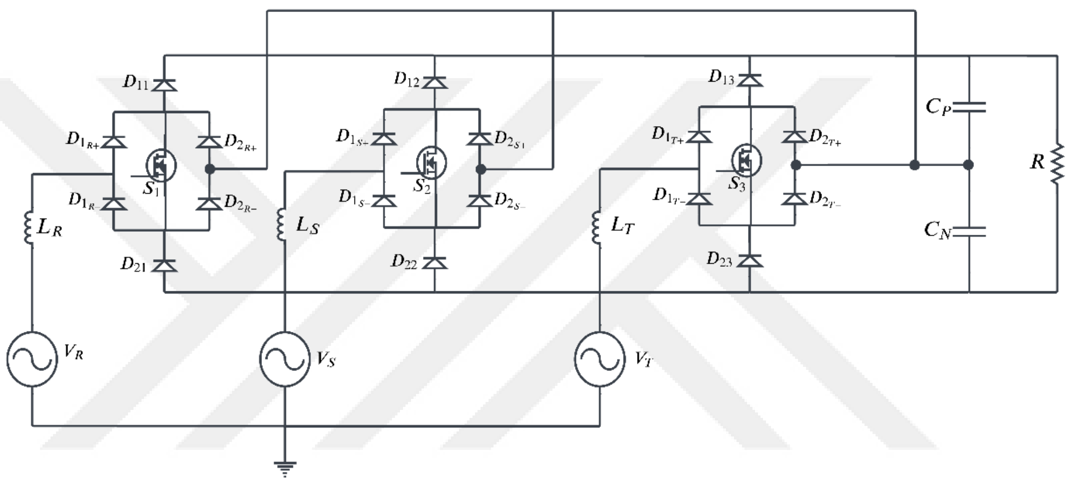


Figure 4.1: Used Three Phase Vienna Rectifier Topology

Operation modes also of the six phases Vienna rectifier, and three phase Vienna rectifier are same because of reducing assumption the phases to single phase. Figure 3.2 represent the operation modes, and operation modes are the same as explained in Section 3.1Operation Modes of Single-Phase Vienna Rectifier..

Inductors and capacitors were chosen as much as common value to compare the inductance ripple and THD values of six phase and three phase Vienna rectifiers. The used semiconductors are the same to compare the power loss, and to detect the thermal effects.

In addition to them, the used control algorithm is the same as six phase Vienna rectifier, hysteresis control.

5. SIMULATIONS AND RESULTS

Six Phase Vienna Rectifier Design circuit was created together with Three Phase Vienna Rectifier to compare these two topologies. Simulations consider also thermal model of semiconductors, and coolant temperature.

The same diodes and SiC MOSFETs are used for both topology, and comparisons are performed in same load conditions.

Simulations were created in PLECS which is developed by company Plexim GmbH, and thermal models are loss calculations are designed in this software as model based development principles.

5.1 Thermal Modelling of a Semiconductors

The using of the steady state thermal resistance values of the semiconductors are not appropriate to calculate the power loss and temperature decreasing or increasing, because of low pulse time from microsecond to milli second [64]. Representation of this short time interval is expressed in time dependent equation

$$Z_{th}(t) = \frac{\Delta T(t)}{P} \tag{5.1}$$

where, $\Delta T(t)$ is the temperature change according to the time, P is the power dissipation because of flow current, and $Z_{th}(t)$ is time dependent thermal impedance. This thermal impedance is modelled with two different networks which are Cauer Network and Foster Network from junction to case or to heatsink of semiconductors.

5.1.1 Cauer network

Cauer Network connects each node to ground through a capacitor.

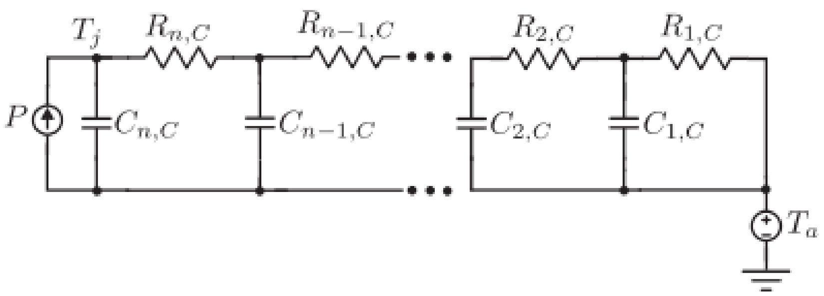


Figure 5.1: Cauer Network

Figure 5.1 shows the Cauer Network. Each capacitance and resistance value is detected by test.

Cauer model of the semiconductor is also known as continued-fraction circuit or T-model or ladder network. Cauer model represents the real, physical setup for semiconductors. Each layer which is included resistance and capacitance reflects the physical setup such as chip, chip solder, substrate. When a semiconductor is modelled according to the Cauer model, temperature difference between different layers are known. Each nodes appeared the related layer temperature [65].

5.1.2 Foster network

Foster Network is representation of the thermal network of a semiconductor connecting the non-grounded capacitance.

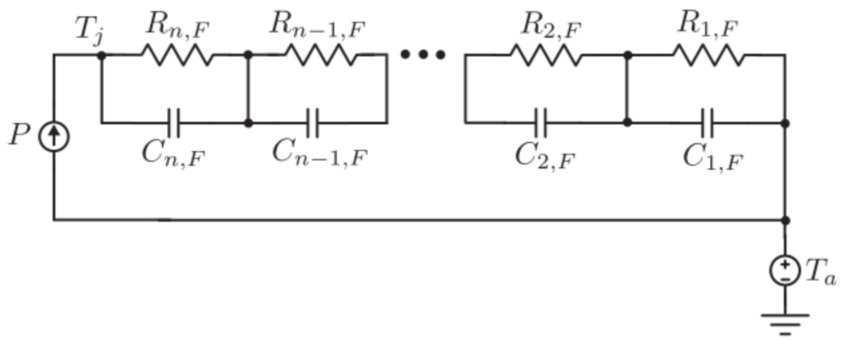


Figure 5.2: Foster Network

Figure 5.2 shows the Foster Network.

The network does not have any physical layer representation. This model is used in datasheets to explain thermal parameters and make calculation analytically. On the other hand, instead of the have measurement for all physical layer, parameters can be generated from cooling curve of module. [65]

Partial fraction model thermal impedance can be expressed as

$$Z_{th}(t) = \sum_{n=1}^{k} r_n(1 - e^{\frac{t}{\tau_n}}) \tag{5.2}$$

where

$$\tau_n = r_n c_n \tag{5.3}$$

and n is index of the layer seen in Figure 5.2, c_n is thermal capacitance, and r_n is thermal resistance. For instance, in a datasheet, basically total impedance graph of module is presented as seen in Figure 5.3. Presented data is all thermal impedance between junction of the module to case, $Z_{th(j-c)}$. Thermal impedance partial fraction terms are 4 layers, and their values is seen as r, it is K/kW, and τ, s.

It is representation of the thermal impedance from case to junction as mentioned above, and when the junction temperature calculation is needed converted equation (5.1) is used as

$$T_j(t) = P_L(t)\, Z_{th(j-c)} + T_c(t) \tag{5.4}$$

Where $P_L(t)$ is instantaneous power loss, and T_c is the case temperature of the module.

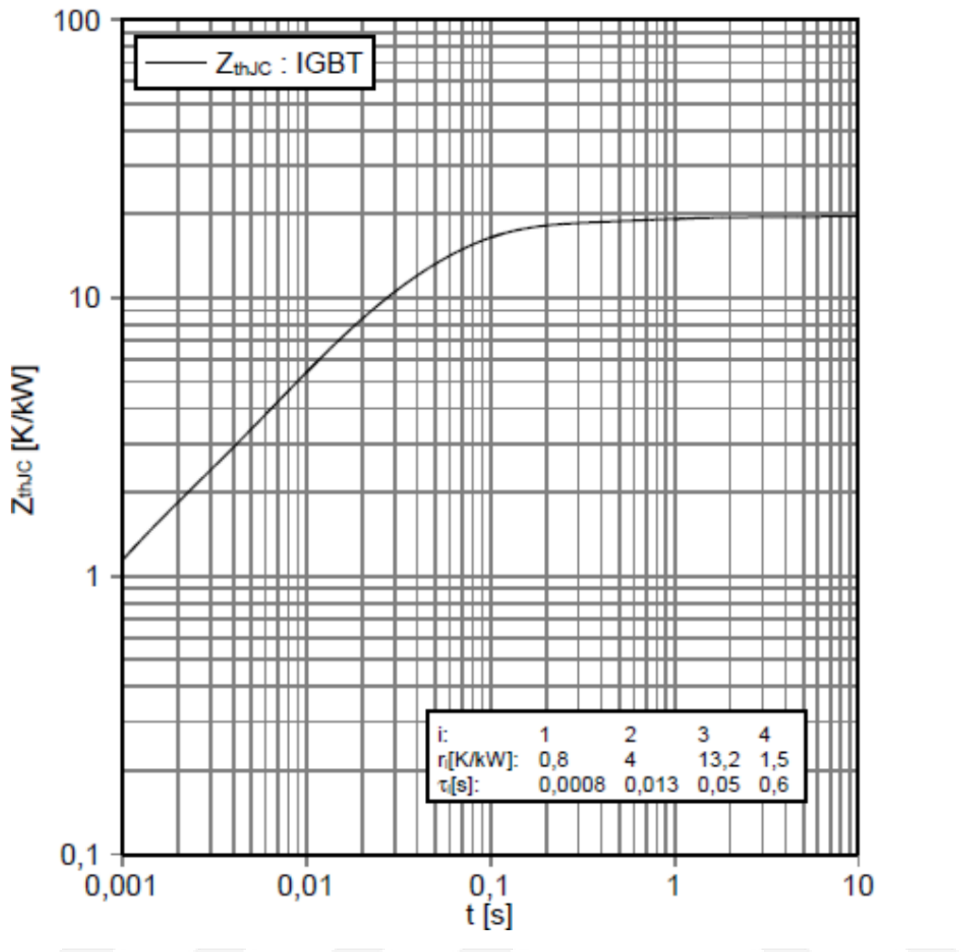
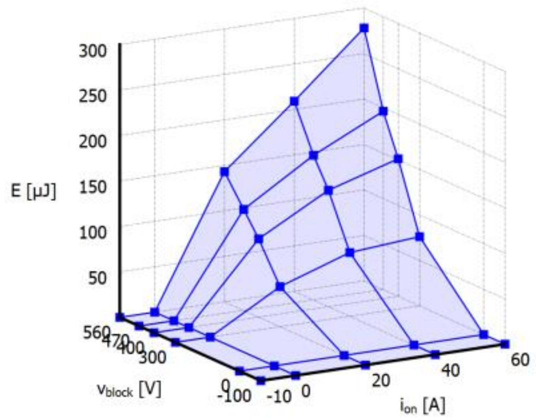


Figure 5.3: Thermal Impedance Specification Example Based on Partial-Fraction Model

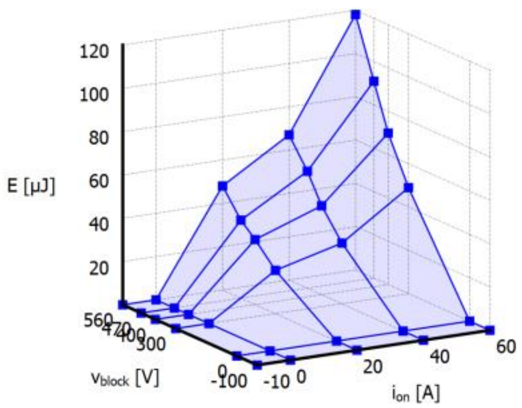
5.2 MOSFET Modelling in Simulation

The used MOSFET in simulation is MSC035SMA070B4. It is silicon carbide based on the new generation MOSFET. Its nominal drain source is voltage V_{DS} is 700V, and current rate I_D is 77A at 25°C case temperature.

MOSFET data is applied to the simulation in PLECS as discrete SiC MOSFET. There are two different type loss in semiconductor based switches. They are switching loss which are turn-on and turn-off loss, and conduction loss while current flow through the switch.



a) Turn-on Loss of MSC035SMA070B4



b) Turn-off Loss of MSC035SMA070B4

Figure 5.4: Switching Energy of MSC035SMA070B4

Figure 5.4 shows the turn-on and turn-off energy of used MOSFET according to the V_{block}, it represents the V_{DS} and i_{on}, it represents the I_D.

Another loss for MOSFETs is conduction loss, and it is resistive based loss.

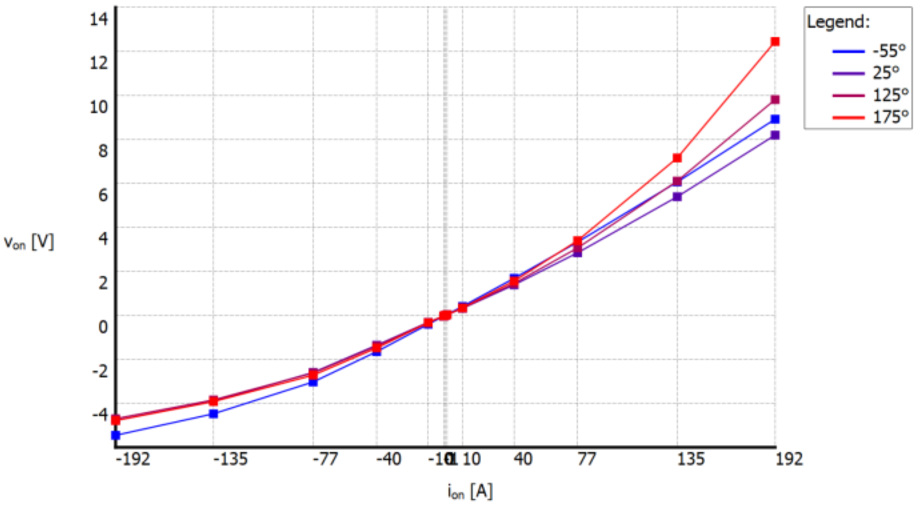
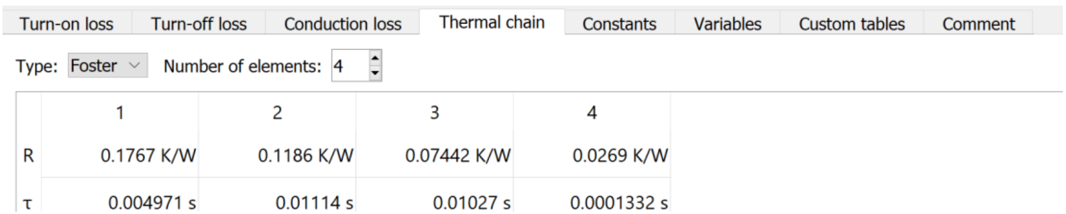


Figure 5.5: Voltage Drop of MSC035SMA070B4 While Conduction

Figure 5.5 shows the voltage drop on MOSFET while it is conduction, depending on the current i_{on} which represents the I_D, and junction temperature.

On the other hand, thermal network of used MOSFET is created as four elements foster model. It means that four resistance, and four capacitor is exist in model from junction to case.



	1	2	3	4
R	0.1767 K/W	0.1186 K/W	0.07442 K/W	0.0269 K/W
τ	0.004971 s	0.01114 s	0.01027 s	0.0001332 s

Figure 5.6: MSC035SMA070B4 MOSFET Thermal Parameters

5.3 Diode Modelling in Simulation

Used diode is MSC050SDA070S. Its maximum reverse voltage V_R is 700V, and nominal DC forward current I_F is 88A at 25 °C.

Diode model only considers conduction loss because there is not switch operation.

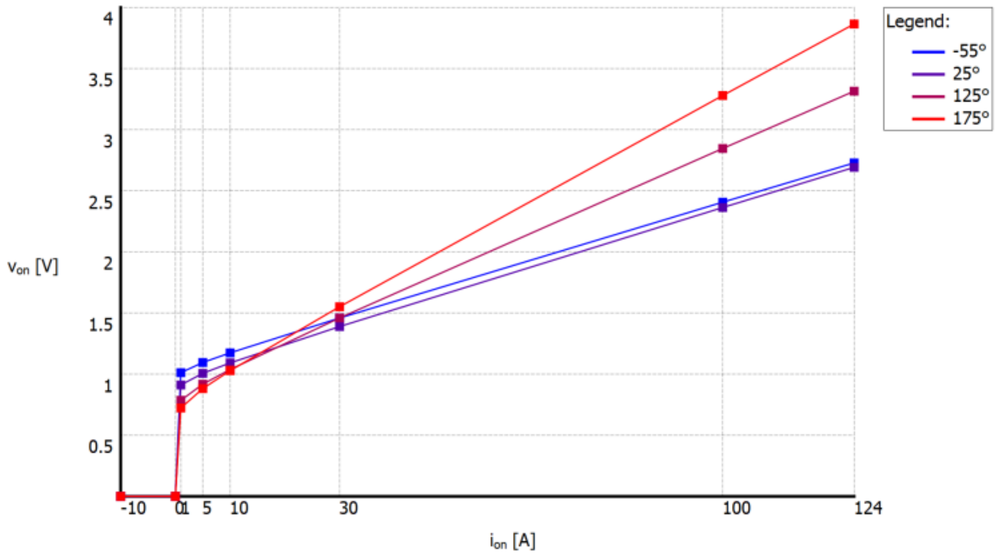


Figure 5.7: Voltage Drop of MSC050SDA070S While Conduction

Figure 5.7 shows the voltage drop according to the flow current through the diode in conduction, and junction temperature.

Thermal model is the same as created in MOSFET. It is four elements foster network model.

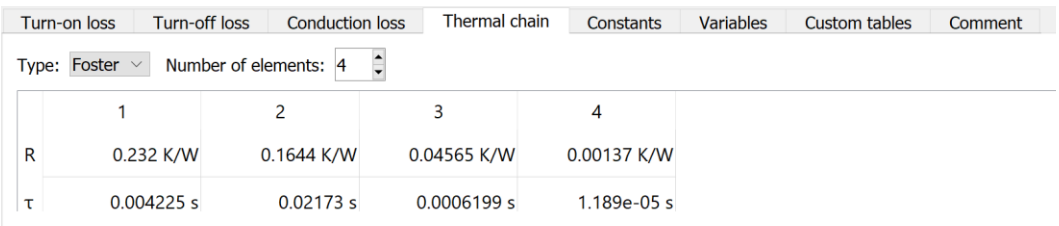


Figure 5.8: MSC050SDA070S Thermal Parameters

Figure 5.8 shows thermal parameters of the diode used in circuits.

5.4 Circuit Modelling

Two different circuits are created in PLECS as three phase and six phase. Figure 4.8 and Figure 4.9 shows the three phase and six phase Vienna Rectifier respectively. Both of the circuits include thermal model of semiconductors, and coolant temperature is fixed as 25 °C.

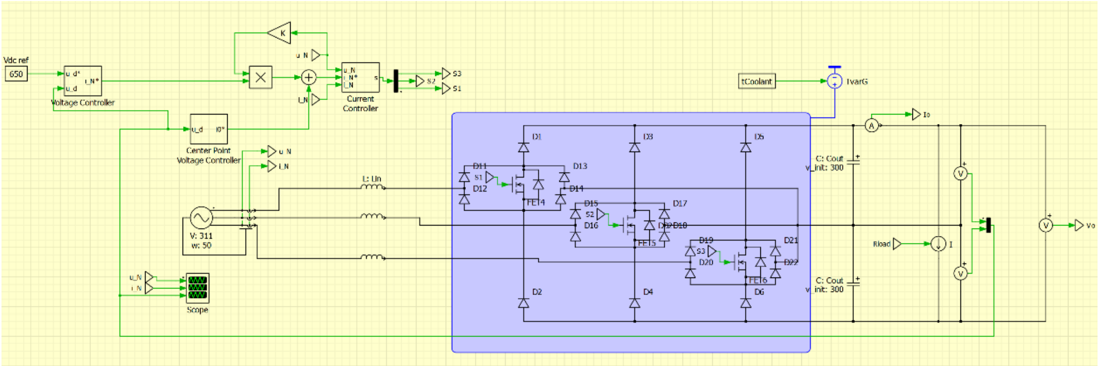


Figure 5.9: Three Phase Vienna Rectifier

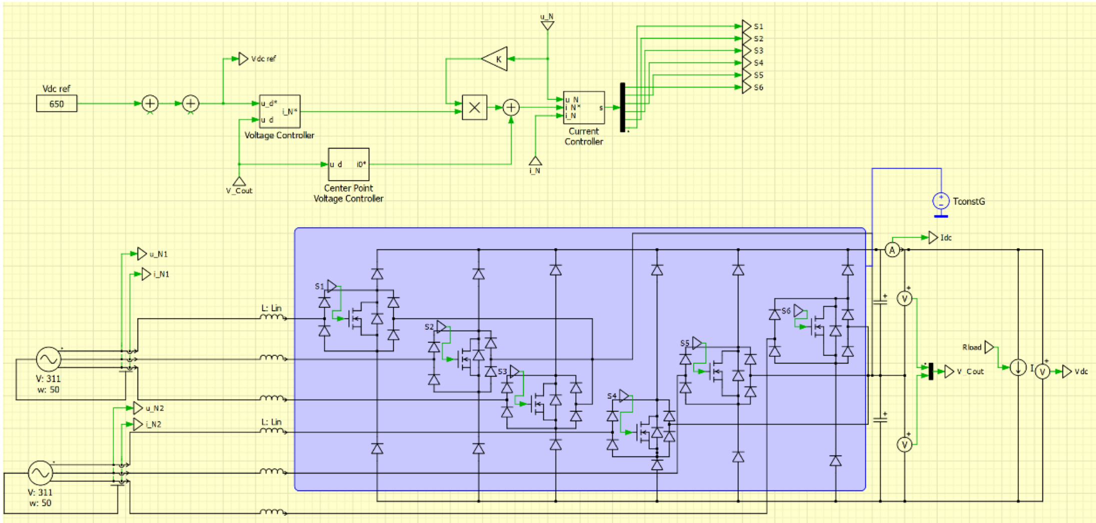


Figure 5.10: Six Phase Vienna Rectifier

5.5 Control Algorithm

Closed loop control was applied, and Hysteresis control was implemented as can be seen in Figure 5.11 including voltage loop, inner current loop, and center point voltage controller for DC filter capacitances. Hysteresis loop caused simplicity for implementations, but switching frequency varies, and hysteresis control does not guarantee keeping the ripple in limited arrange while it is implemented by digital controllers.

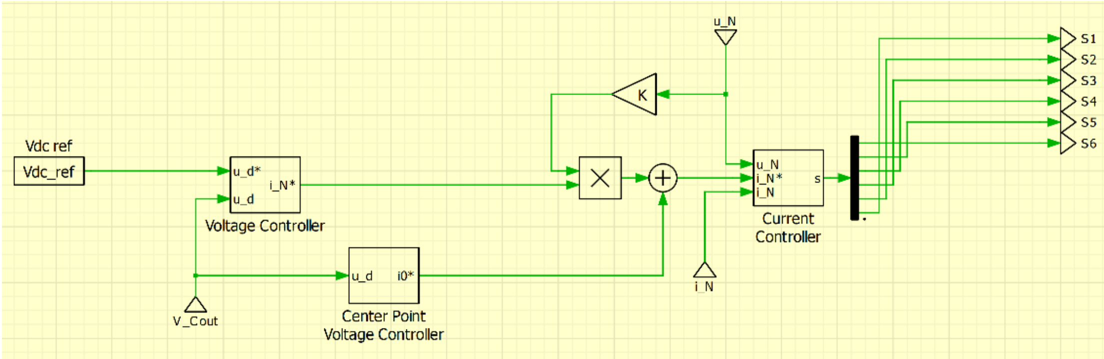


Figure 5.11: Hysteresis Control Loop

For error compensation, continuous PID controllers were used as seen in Figure 5.12 and Figure 5.13 for voltage and center point voltage controller.

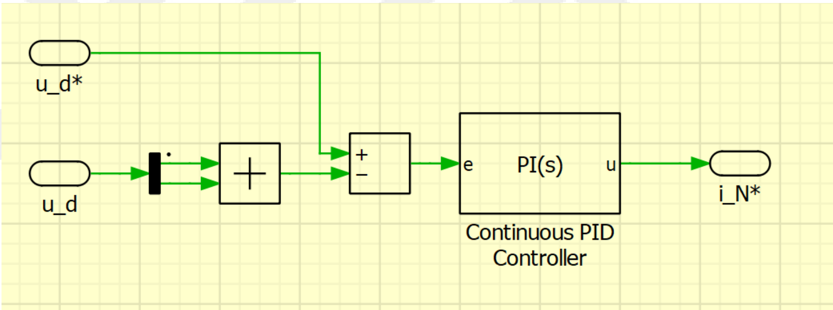


Figure 5.12: Voltage Control Loop

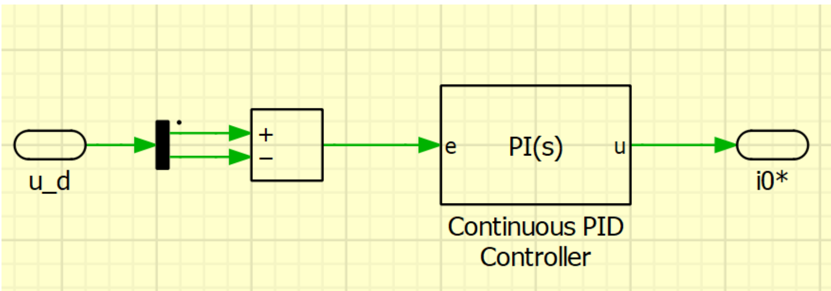


Figure 5.13: Center Point Control Loop

Figure 5.14. shows the Hysteresis controller. The relay sets and resets according to the determined positive and negative limits of the current, and this helps to keep the inductor current ripple or current error at a low value.

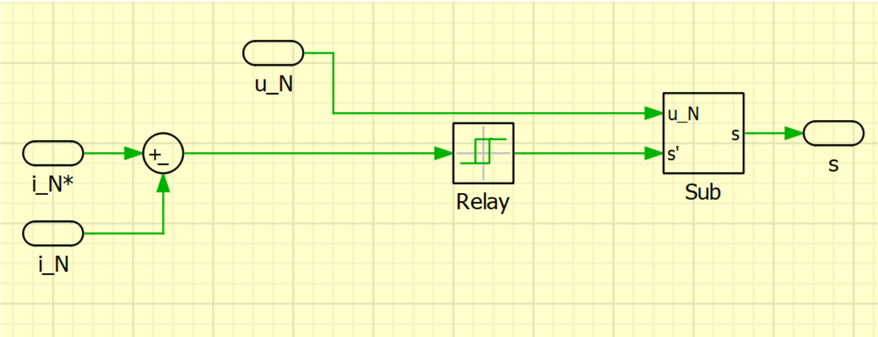


Figure 5.14: Current Controller Loop

5.6 Simulation Results and Comments

Firstly, control algorithm performance analysis was performed. Voltage references are changed with step and ramp as seen in Figure 5.15, and Figure 5.16 for three phase and six phase Vienna rectifier, respectively. Four different scenarios in one simulation period were applied. The ability of the control method to follow the reference voltage while the voltage reference and load current changes according to the scenario was analyzed.. The first event began with the application of 700 V reference voltage and the rectifier was loaded with 14 kW constant load (constant current as 20 A). Then the reference voltage was ramped to 750 V and the load was increased to 15 kW. After 750V reference and 20A load voltage reference stepped to 800V for 20A load and power is set to 16kW. While load is 16kW, the load current is decreased to 10A for 800V reference. All voltage reference changes details are seen in Figure 5.17, and Figure 5.18 for three phase and six phase Vienna rectifier topologies, respectively. On the other hand, load change and its effect for three phase and six phase Vienna rectifier was visualized in Figure 5.19.

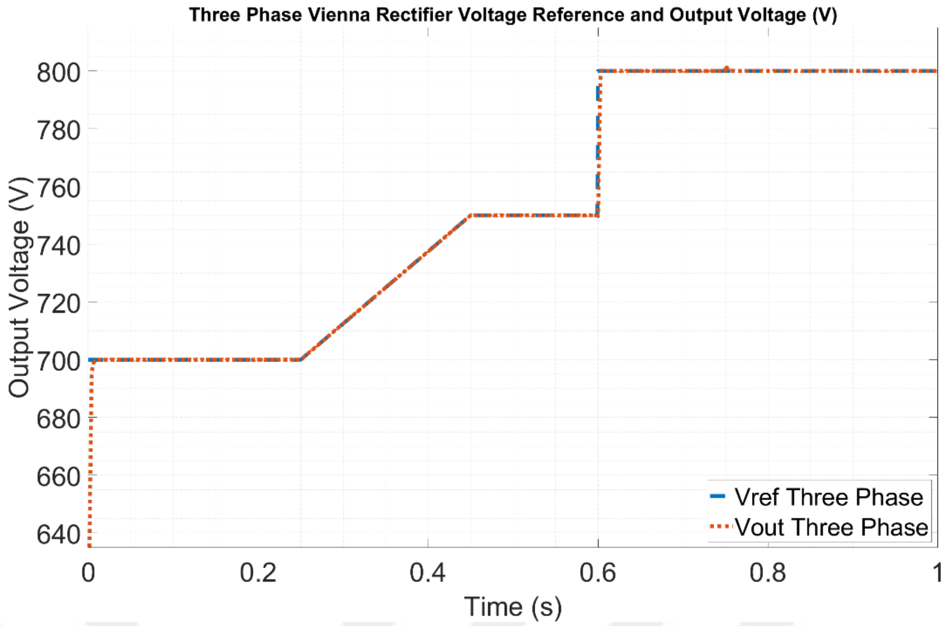


Figure 5.15: Voltage Reference Change and Tracking for Three Phase Vienna Rectifier

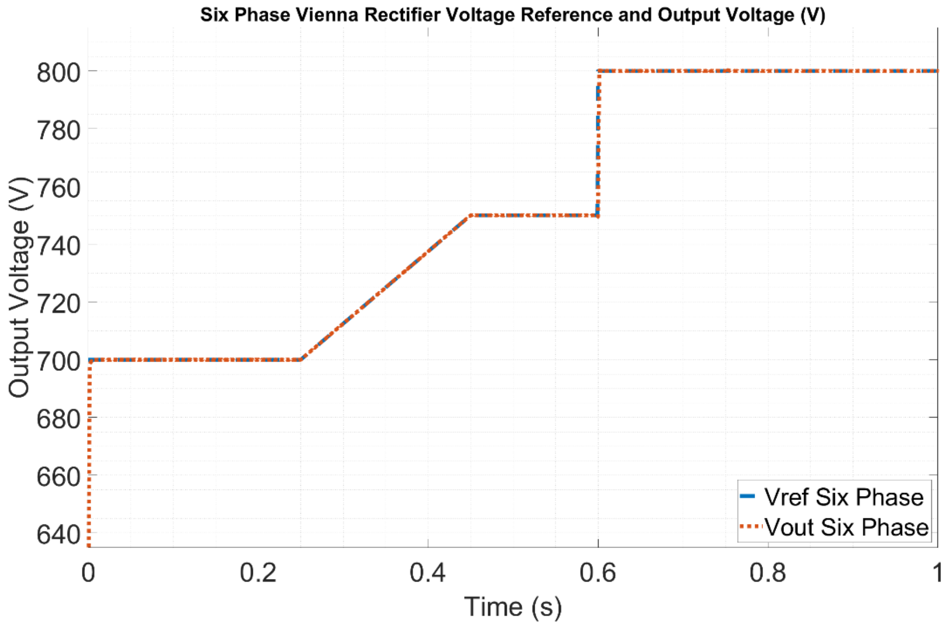


Figure 5.16: Voltage Reference Change and Tracking for Six Phase Vienna Rectifier

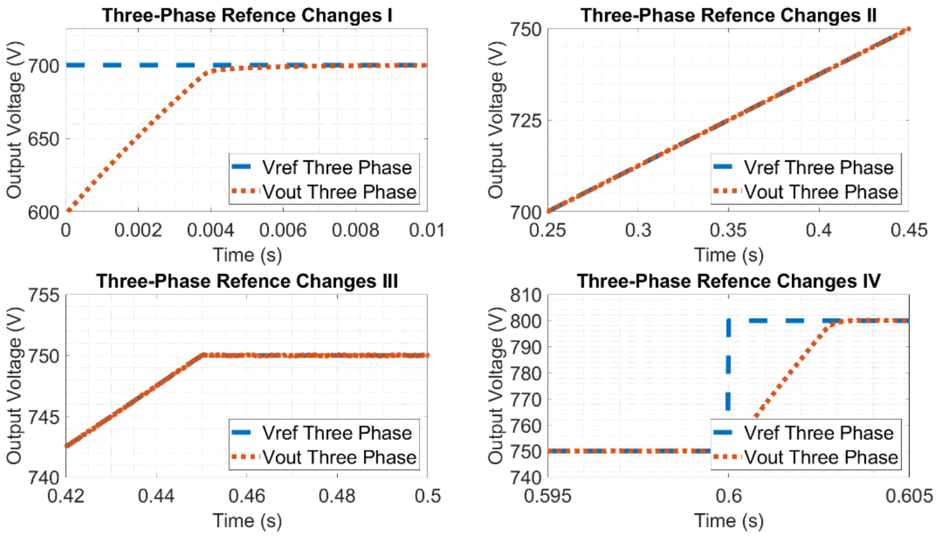


Figure 5.17: Voltage Reference Change in Three Phase Vienna Rectifier

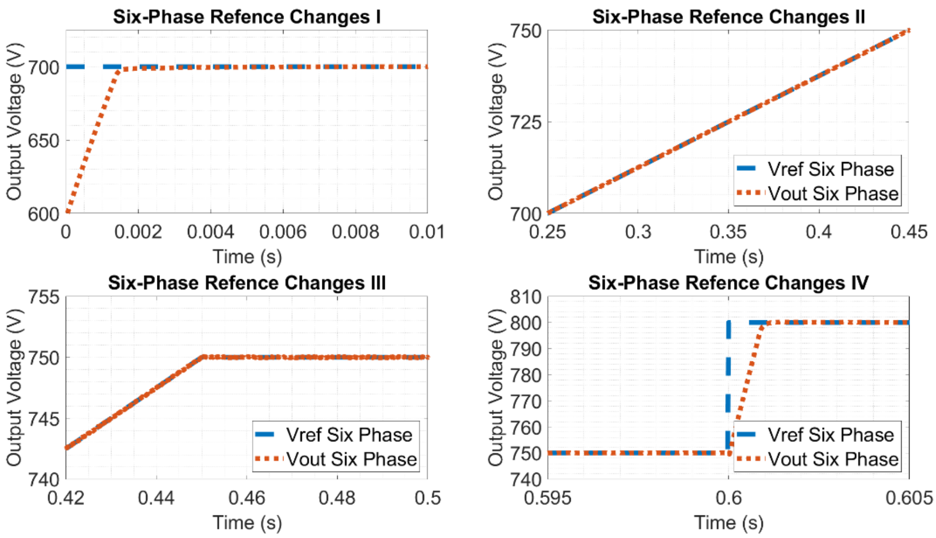


Figure 5.18: Voltage Reference Change in Six Phase Vienna Rectifier

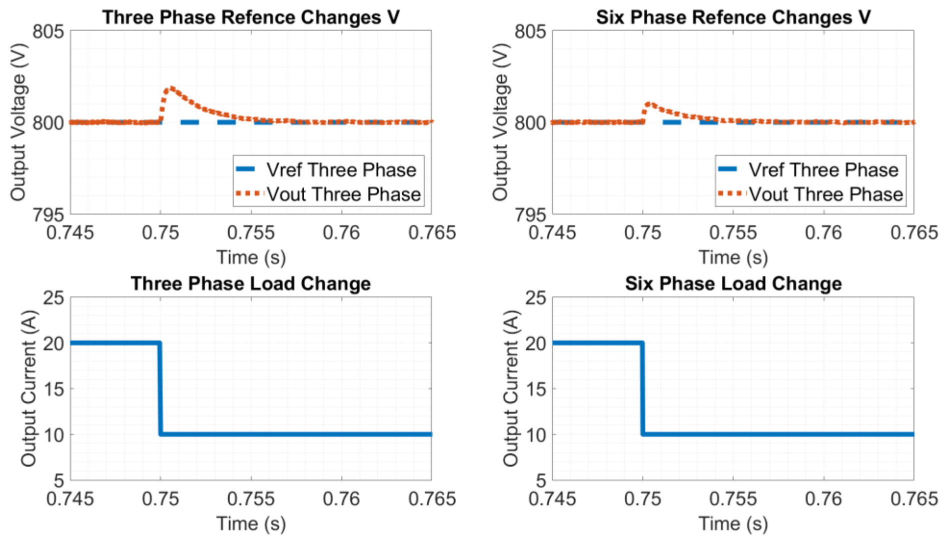
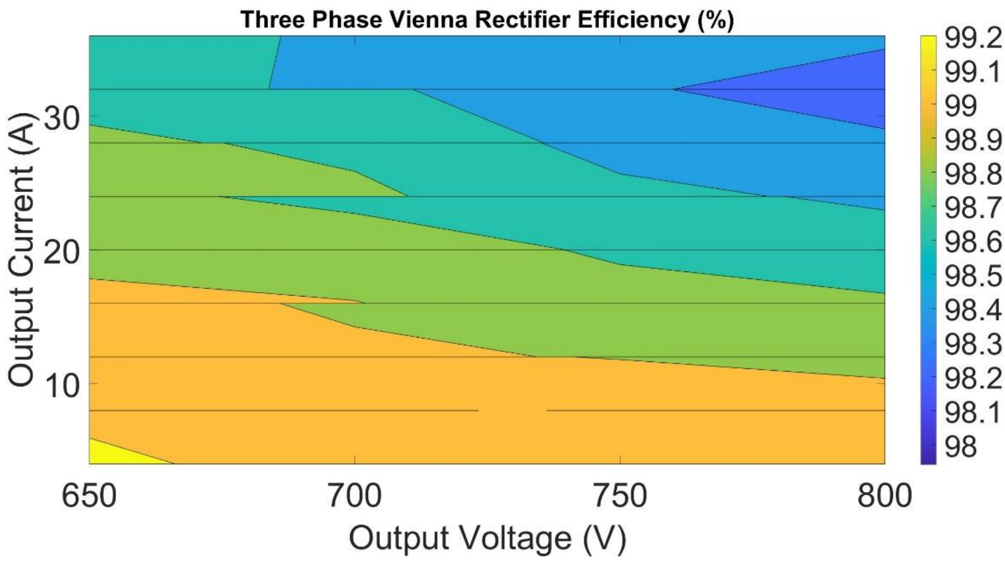


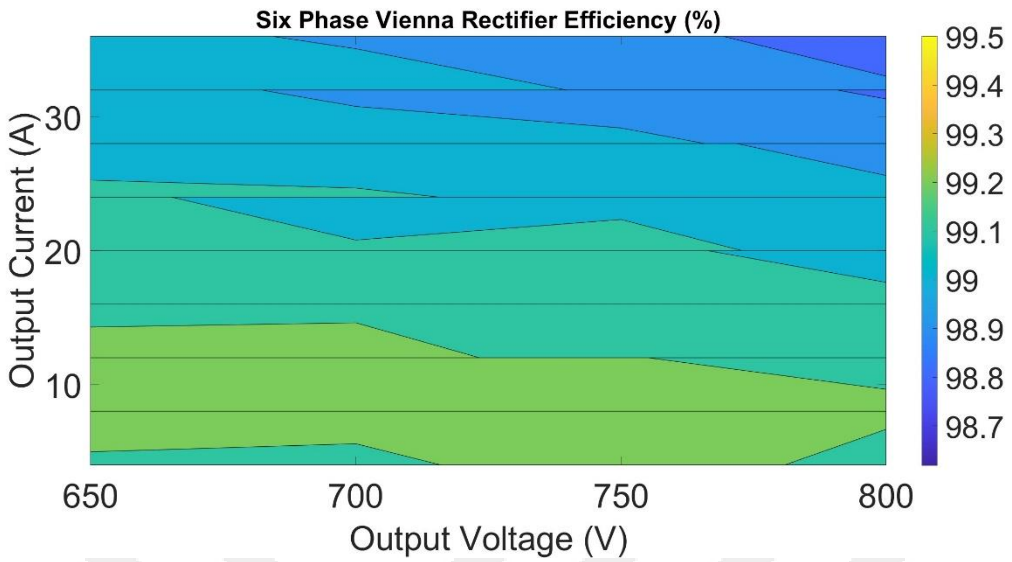
Figure 5.19: Load Change While Voltage Reference Is Constant

Further, simulation scenarios are created with different loads and different voltage levels by combination of them. Voltages levels were defined as 650V, 700V, 750V 800V; and current levels were as 4A, 8A, 12A, 16A, 20A, 24A, 28A, 32A and 36A. Thus, the minimum output power is 2600W, and maximum output power is 28800W.

Figure 5.20 shows the efficiency of the rectifiers. Three phase Vienna rectifier's minimum efficiency is 98.1, and six phase Vienna Rectifier efficiency is 98.8. According to these maps, nominal power dependent the most efficient rectifier topology between three phase and six phase Vienna rectifier is able to detect.



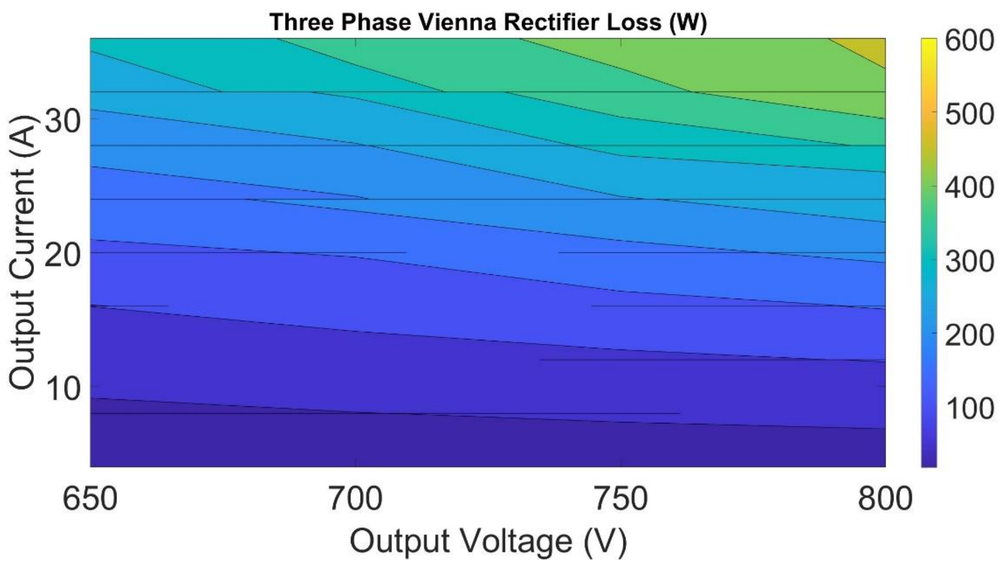
a) Three Phase Vienna Rectifier Efficiency Map



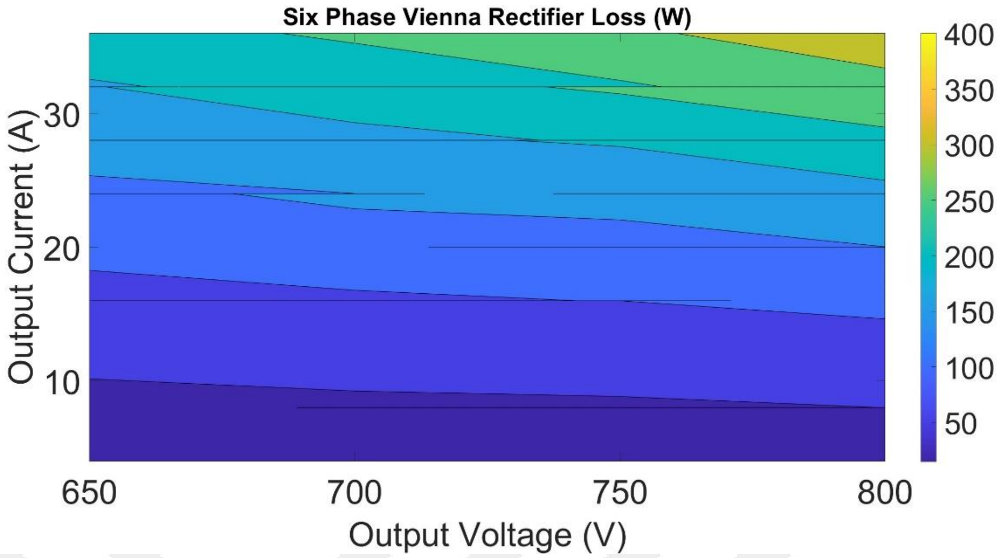
b) Six Phase Vienna Rectifier Efficiency Map

Figure 5.20: Rectifiers Efficiency Maps

The explaining of the efficiency through another way is losses of the semiconductors. Thera are two different losses which are switching losses and conduction losses in switching semiconductors. Diodes have only conduction losses. Total loss of a rectifiers for three phase and six phase are shown in Figure 5.21. Maximum loss of the three-phase rectifier is 600W, but these value is 400W for six phase rectifier.



a) Three Phase Vienna Rectifier Total Semiconductor Loss Map

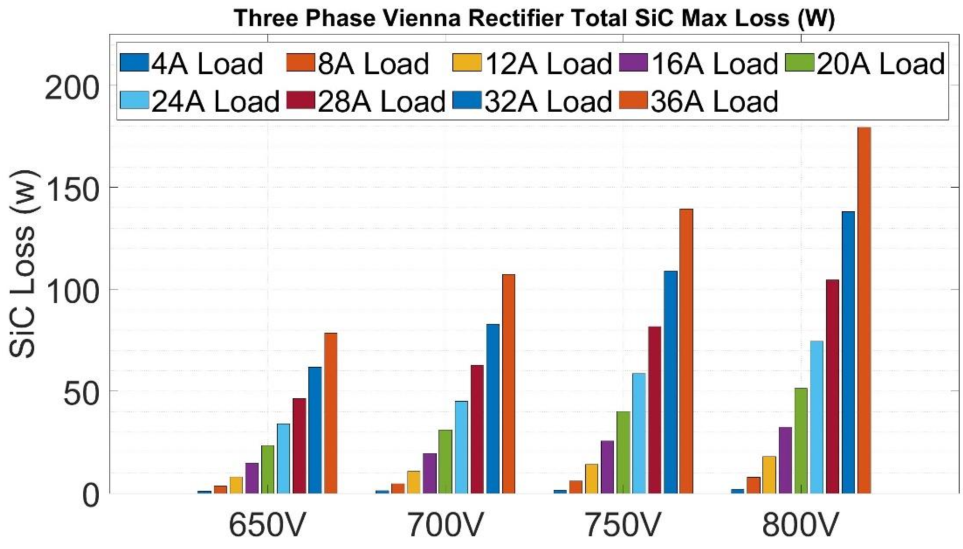


b) Six Phase Vienna Rectifier Total Semiconductor Loss Map

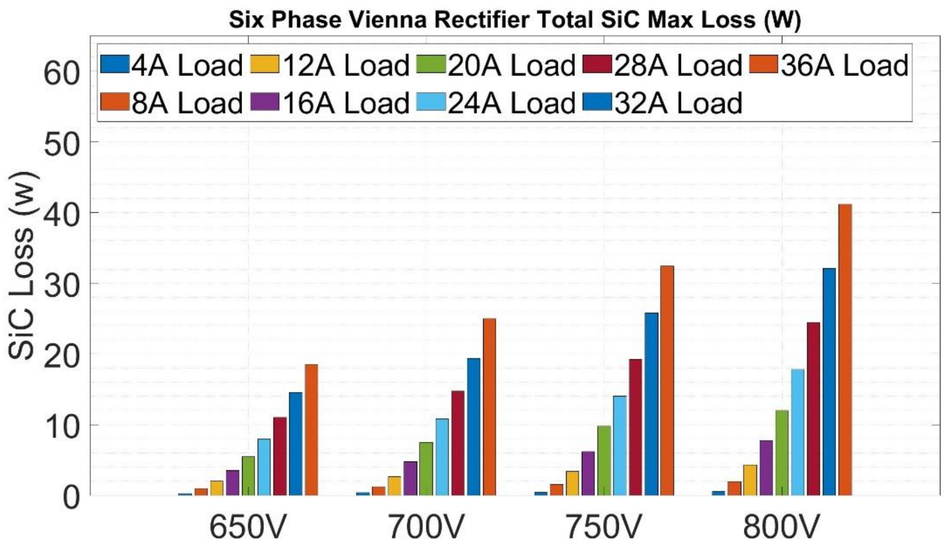
Figure 5.21: Rectifiers Total Loss Maps

On the other hand loss maps show that three phase rectifier has in greater numbers region in loss map. Designers should be careful while choosing converters for the systems which deviate from their nominal power rates. If this deviation number is much, six phases might be more efficient even in nominal power is more efficient for three phase.

These losses come from semiconductors switches, and Figure 5.22 shows the one SiC switch losses for three phase and six phase Vienna rectifiers. This figure shows the switching losses and conduction losses summation.



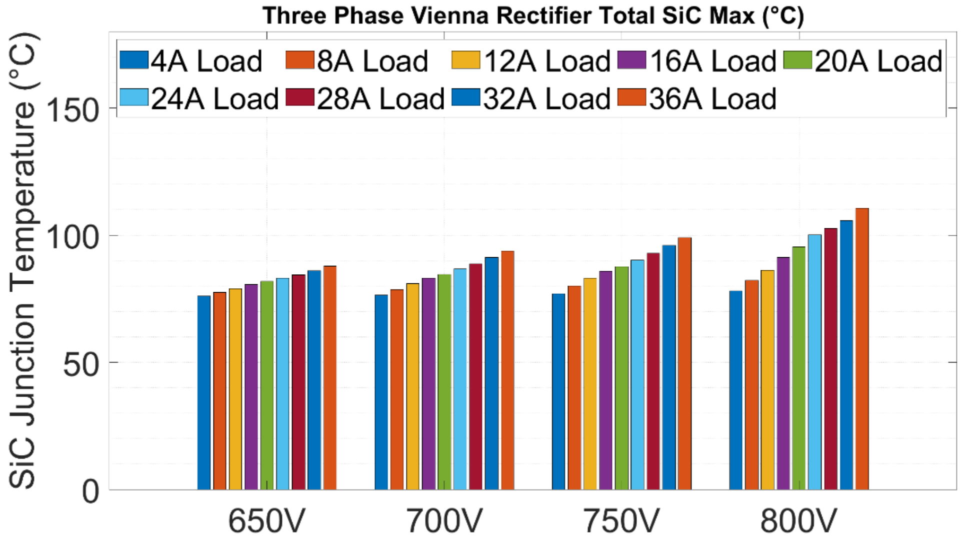
a) Three Phase Vienna Rectifier One SiC Switch Loss



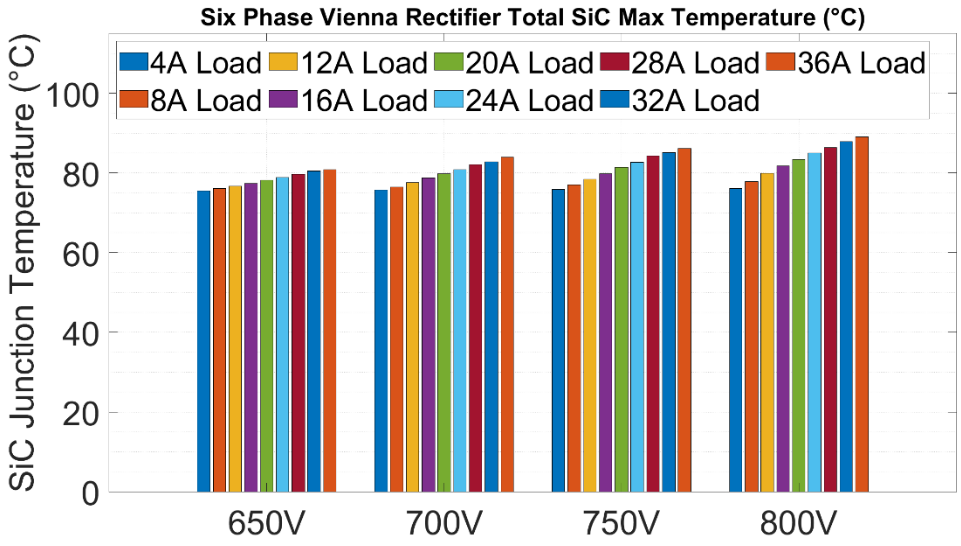
a) Six Phase Vienna Rectifier One SiC Switch Loss

Figure 5.22: Rectifiers One SiC Switch Loss

In high power demand, switches have more stress. As each switch power loss can be seen in Figure 5.22 , junction temperature of the each SiC switches can be seen in Figure 5.23. According to the PLECS thermal model of MSC035SMA070B4 SiC switch, the coolant temperature is kept as 75 ℃, and rectifiers are simulated. Manufacturer of the MSC035SMA070B4 already defined the maximum junction temperature is 175 ℃. Operations in risk area reduce the life time of the component.



a) Three Phase Vienna Rectifier One SiC Switch Temperature

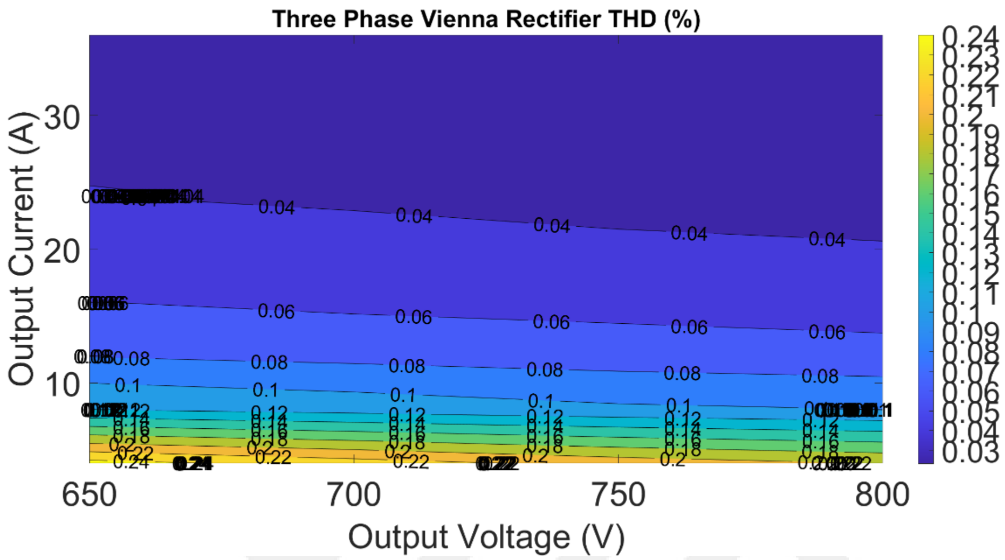


a) Six Phase Vienna Rectifier One SiC Switch Temperature

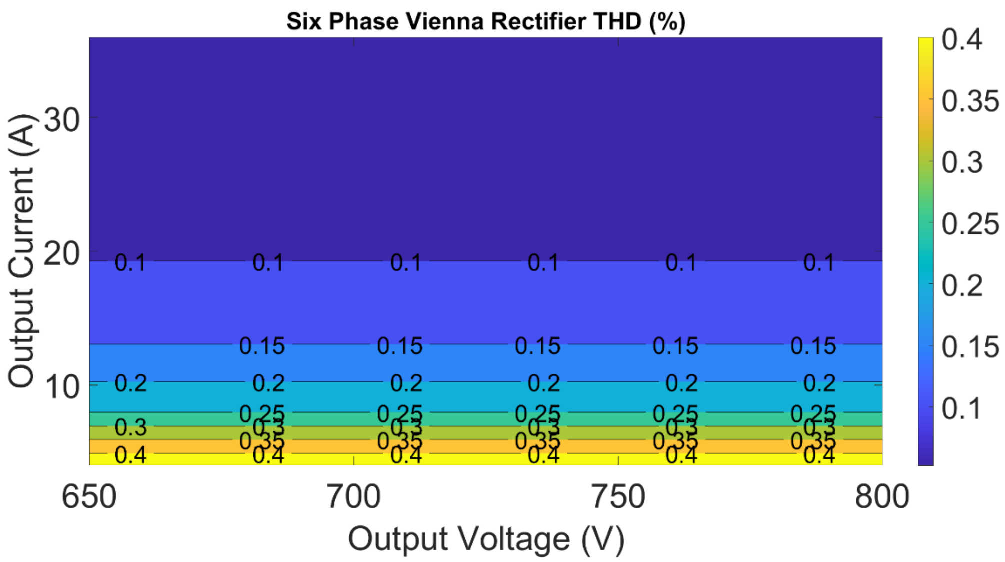
Figure 5.23: Rectifiers One SiC Switch Temperature

An important note must be added that Figure 5.22 and Figure 5.23 shows the maximum point of each period of input current. Temperature difference does not change dramatically, but power losses change as sinusoidal, and it depends on to the polarity of the current. In other words, all of the diodes are not in operation continuously.

Another important parameter of the rectifiers is total harmonic distortion (THD) of the source current. Source is connected to main network, or main suppliers constitutively, and rectifying of source through switches with different frequencies affects the source current. This effect deforms the source current shape and creates different frequencies in draw current. In simulation, any compensation was not professed to have better result for THD. THD results of the rectifiers are shown in Figure 5.24.



a) Three Phase Vienna Rectifier THD



b) Six Phase Vienna Rectifier THD

Figure 5.24: Rectifiers THD

Three phase Vienna rectifier gives better quality THD results because of the drawn current per inductor. THD is related about harmonics in input current as mentioned above, hence input currents wave analysis is able to help to understand THD, easily.

In Figure 5.25 and Figure 5.26 input currents waves of phase A for three phase and six phase Vienna Rectifiers are seen, respectively.

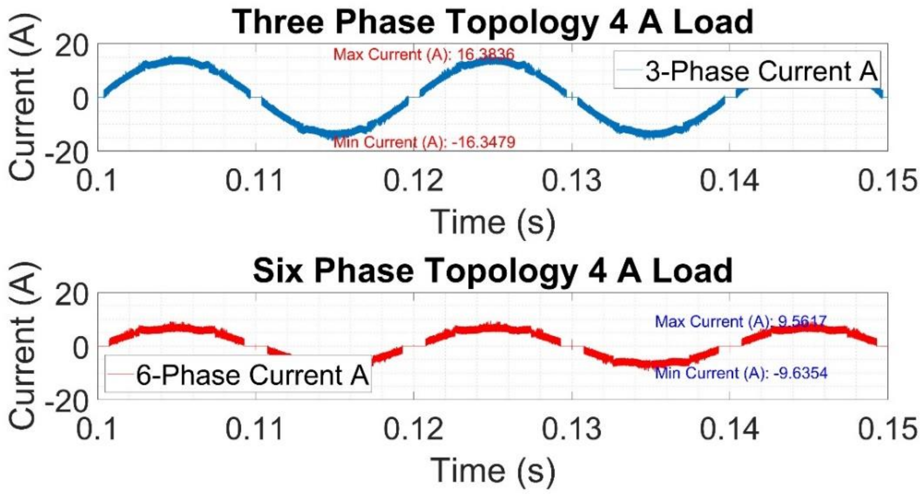


Figure 5.25: Phase A Currents for 4 A Load

In comparison of the same load of rectifiers for three and six phases, three phase current drawn is more than the six phases per phase because of less phases number. As seen in Figure 5.25, phase current waves for three phases are more symmetrical in light loads. It already means that less THD as seen in comparison Figure 5.24.

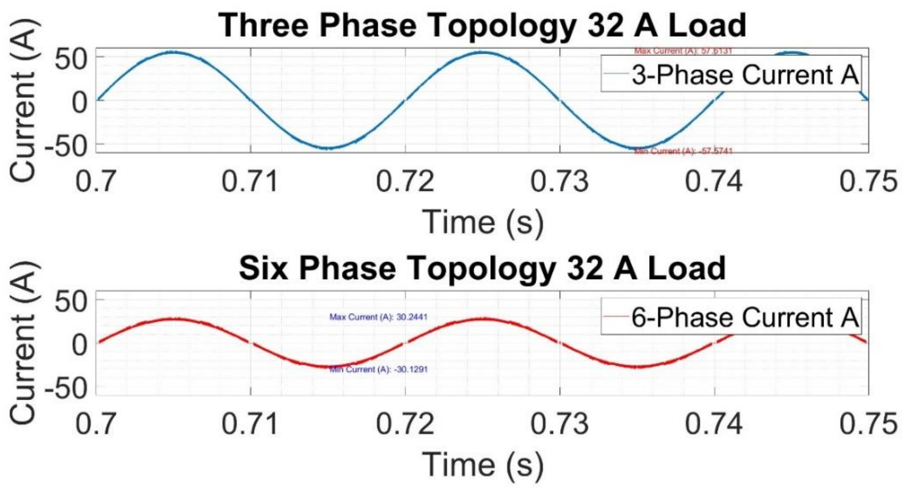


Figure 5.26: Phase A currents for 32 A Load

On the other hand, currents are more stable for high loads because of the higher drawn current per inductors or phases. Passing from the zero for currents are more smooth in three phases when it is compared with six phases, because of it we have less THD. It is already seen in Figure 5.24.

6. CONCLUSION AND RECOMMENDATIONS

In this study, a six-phase Vienna rectifier I design was implemented in a simulation environment. To see the effects of the six-phase Vienna rectifier on THD, power loss, and temperature, another rectifier capable of carrying the same power was designed with three phases. The components used are the same for the six-phase and three-phase models, and simulations were run for the same current and voltage points for the same power level.

The simulation environment was set up in the PLECS software developed by Plexim GmbH. The thermal models of the diodes and MOSFETs used were entered as input into this software environment, and the results of losses and temperature change were recorded. The case temperature was kept constant at 75 °C to be the possible difficult conditions.

Hysteresis control was used as the control strategy. The difference current signal was converted from the voltage error and applied to the hysteresis band input current reference. In addition to this main body control, the voltage difference between them was continuously monitored and included in the control algorithm to ensure that the voltages of the output filter capacitors are equal. No special algorithm implementation was made for THD compensation.

As a result, it was observed that the total loss of the six-phase Vienna rectifier decreased compared to the three-phase Vienna rectifier as the total power drawn from the source increased, and the maximum point that the temperatures of the diodes and MOSFETs, which are semiconductors, could reach decreased. However, THD levels gave better results in the three-phase rectifier. Because the current requirement drawn per phase has increased, which has also reduced the duration of harmonics formed at zero transitions in three-phase.

As the next step of the study, power loss, THD, and temperature comparisons can be repeated by applying state space vector switching for six-phase and three-phase Vienna rectifiers. In addition to the comparison of three-phase and six-phase Vienna rectifiers, controlled three-phase rectifier and six-phase rectifier can be compared by controlling hysteresis control and state space vector switching. Thus, it can be determined whether the control strategy also has effects. In addition to these, by adding compensation for THD, which topology will be more advantageous when THD levels are improved can be compared.

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