A Medium Voltage Cascaded Multi-level Converter with Isolated High Frequency Link Using SiC Switching Devices.

A Thesis

Presented to

The Faculty of the Department of Electrical and Computer Engineering
University of Houston

In Partial Fulfillment
Of the Requirements for the Degree
Masters of Science
In Electrical Engineering

by

Alaba Esho

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A Medium Voltage Cascaded Multi-level Converter with Isolated High Frequency Link Using SiC Switching Devices.

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ABSTRACT

In this thesis, a new medium voltage multi-level power converter using low voltage SiC devices that would result in an overall efficiency improvement in harnessing renewable energies was analyzed. The topology is based on cascading low voltage power stages that utilize isolated DC-DC converter. The units to be improved are the DC-DC converter, which was used in conjunction with a rectifier (depending on the nature of the renewable energy source- AC or DC power source) and an inverter at the output stage. The DC-DC converter is a Dual Active Bridge with a high frequency link; the high frequency link is possible based on the high-frequency transformer (HFT) and wide band gap switch (silicon carbide (SiC) MOSFET) that was adopted in this topology. Due to the inverse relationship between frequency and the size of magnetic components, the power density of the converter is high, which in-turn gives a higher efficiency. Apart from these benefits, there are a number of advantages in this topology such as the isolated link, the multilevel output, the variable frequency output, the compatibility with High Voltage Direct Current (HVDC) etc. In this case, the generation units could be offshore or in a remote on-shore area due to environmental or aesthetic reasons. One of the major factors that discourage harnessing of renewable energy is the initial cost involved; the topology chosen naturally minimizes the number of components involved and this, in turn, reduces the cost and the failure rate. The final output is a high power quality multilevel AC voltage with low concerns for electromagnetic compatibility. The Simulations were carried out using a library in MATLAB (Simelectronics/Simscape).

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CHAPTER 1 INTRODUCTION

1.1 Background

In recent years, there has been a drastic improvement in the development of renewable energy power conversion schemes. This is partly due to an increase in the consumption of electricity in the world, the inherent nature of humans to provide different options/ways of solving problems, environmental reasons (global warming due to greenhouse gas emissions and public health risks etc.) and unavoidably, the limited amount of the conventional sources of energy such as fossil fuels. Different researchers have worked and are presently working on improving the power conversion technologies to harness renewable energies. The choice of area of research is rooted in my high interest in power and power electronics in electrical engineering, which is a function of my working experience in utilizing power equipment paired with the theoretical knowledge garnered overtime. All these triggered the decision to delve more into the science of the make-up of existing power electronics equipment and possible improvement in the technologies involved.

There are different steps in power conversion: transforming renewable energies to a form that is usable by end-users which could be a commercial, industrial or a residential consumer. Depending on the area of specialization of researchers, there are completed work and ongoing work in the different sections involved. For example, in addition to the electrical engineers, the structural engineers, geographical and environmental professionals are always working on the best location and positioning of the machines and equipment that would effectively and efficiently interact with the sources of energy such as solar panels for solar energy, wind turbines for wind energy, steam turbine for geothermal energy etc.

The output of these equipment varies, depending on the nature of the source of energy and the energy collector, for example, a solar panel's output is DC, a wind turbine output is AC and same as a steam turbine. These bring into play the research work in a different section, which is the conversion of the output into a required output depending on the load. Another area is the mode of transmission over a specific distance from the grid to a point of common coupling or directly to the end user in some cases. Some loads like telecommunication equipment and other industrial loads use DC power directly and might need a DC-DC converter and an AC-DC converter or just one of them, depending on the distance from the grid, the type of transmission (AC or HVDC) and some other factors [1]. It is this stage that we are concentrating on as this is where our area of research is of importance. In order to increase the overall efficiency of the whole system, the efficiency of the converter to be adopted at this stage is very key as it contributes a great deal to the overall success in harnessing the energy from renewable sources.

For the converter, a dual active bridge converter is adopted with a different kind of switch called the silicon carbide (SiC) MOSFET. SiC MOSFET is an amazing new technology offering new levels of performance for switching power converters. This is due to its inherent property, which makes it applicable under higher temperature, frequency, and power compared to the existing switching devices. The question that comes to mind is “Why SiC?”. It is a very hard material with a wide band gap ranging from 2.96 to 3.3eV and this affords it special properties for applications in optoelectronic, high-power and high frequency devices. This switch is suitable for high voltage applications, thereby covering for its own downside, which is the forward voltage value of about 1 to 1.3V [2].

CHAPTER 2 LITERATURE REVIEW

Converting DC voltages at a certain level to another level can be achieved by different means, the easiest and least complex being the basic voltage divider. This was achieved by using resistors, capacitors and inductors together or separately to achieve a decrease in voltage levels. One would ask why we go through all these recent troubles and complex topology if it can be this simple. This question brings us back to the reason behind trying to achieve the best efficiency achievable in the DC-DC converter topologies which would translate into an overall increase in efficiency of the system in which it is being used [3]. A better description will be given as follows starting from the basic voltage divider as mentioned above.

2.1 Basic Circuit Voltage Converter

2.1.1 Voltage Divider

This is a basic method used in circuit analysis to convert voltage from a level to a lower level by playing around impedance values which could be purely resistive, inductive, or capacitive or even a combination of any depending on the application. An example of a typical application is seen in the capacitor controlled voltage transformer where an arrangement of capacitors is used to step down the voltage level of a transmission line to a level usable by the relay for metering or operating a protective relay. The basic formula is given below and a diagram showing the mentioned application is also shown in Figure 1, a capacitor voltage transformer, whose primary application is in power system protection circuits. It is mostly used alongside relays for stepping down voltage as mentioned above.

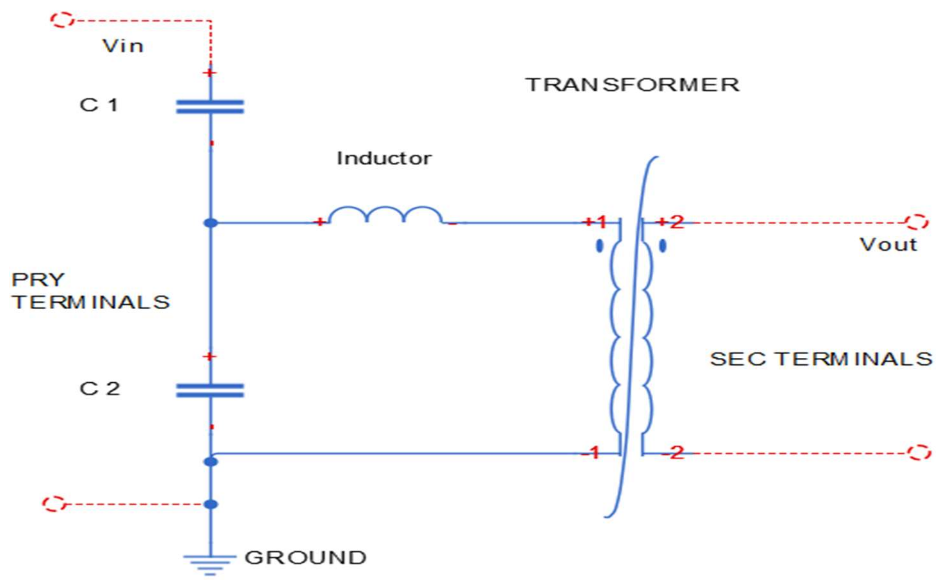


Figure 1: Capacitor Voltage Transformer Circuit

The output voltage is expressed as

$$Vout = Vin\left(\frac{Xc1}{Xc1+Xc2}\right) \quad (1)$$

and

$$Xc = 1/2\pi fC. \quad (2)$$

2.1.2 Linear Voltage Regulator

The above-mentioned method gives an output that is somewhat fixed and inflexible, this paved way for a more flexible method in which the output can be varied as required. In Figure 2, the linear voltage regulator's output voltage is controlled by controlling the load current with the transistor. The transistor base current is varied which in-turn can help vary the output voltage over a particular range. This transistor can be viewed as a variable resistor that operates linearly and never in the saturation or cut-off region [1]. This voltage regulator can be used where a continuous voltage variation rather than a step or discrete variation is required, such as a light dimmer circuit.

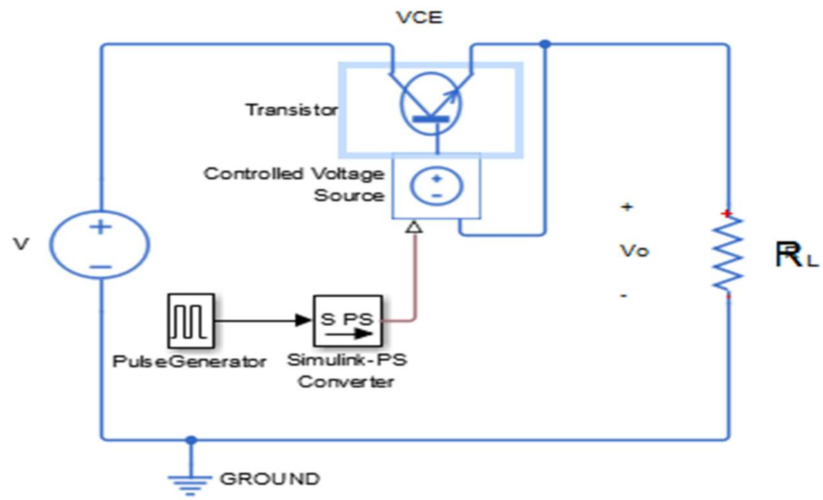


Figure 2: Voltage Regulator Circuit

The two fundamental ways of converting DC voltages mentioned above are of extremely low efficiency, defeating one of the major factors that determine a good design. For example, in the linear voltage regulator, if the output voltage is 30% of the input voltage, the remaining 70% will be absorbed by the transistor as loss and this makes it suitable for low voltage applications alone despite it being better than the basic voltage divider mentioned earlier [1]. The same circuit above can be made to operate as a switching converter by making the transistor work in either a completely off or on position, thereby reducing the loss in the system. These are the reasons for the continuous improvement by researchers which has paved way for a number of topologies when it comes to converters. The other existing switching converters to be presented are divided into two sections, namely:

1. Electrically connected switching converters.

2. Electrically isolated switching converters.

2.2 Electrically Connected Switching Converter

These are switching converters that primarily consist of inductors, switches, and diodes. A very important factor in these converters is the duty cycle, which is a fraction of the period in which the switch is on. It is given as

$$D = Ton/(Ton + Toff) \tag{3}$$

and

$$D = \frac{Ton}{T} = Ton \cdot f, \tag{4}$$

where D is the duty cycle, f is the frequency, T is the period, T_{on} is the ON-time of the switch and T_{off} is the OFF-time of the switch. The output voltage is a function of the duty ratio of the switch, i.e., the pulse width. Assuming the components are ideal, the power absorbed by the ideal switch is zero. There is no current in the switch when in the off state and also no voltage drops when in the on state, although this is not the case for real switches. Losses cannot be averted in real switches because the voltage across it will not be zero when it is on, and the switch must pass through the linear region when making a transition between the two states (ON and OFF). Below are the brief explanations of some common basic switching devices [4].

2.2.1 Buck Converter

A relatively detailed explanation of the Buck converter will be done here in order to understand how the different components operate during the turn on and turn off condition of the switching device. Apart from the source and the load, this consist basically of a switch, a diode, an inductor and maybe a filtering capacitor.

This converter produces a much better DC output than the linear voltage regulator even though the later can be used to control some loads whose output needs to be varied continuously but the fact still remains that the primary motive of a DC-DC converter is to provide the purest form of DC output possible [1]. This converter is assumed to be ideal for calculations most times and also in simulations but that's not the case for real devices. For example, the switch and the diode have zero voltage drop when on and zero current flow when off and the inductor has zero series resistance when they are assumed to be ideal. In the simplest form, this converter is operated by controlling the current through the inductor by using two switches- an inductor and a diode.

This design can be analyzed in two different modes namely the ON and the OFF mode, this is shown in Figure 3. A schematic of a sample simulation is also shown in Figure 4 while the output is shown in Figure 5.

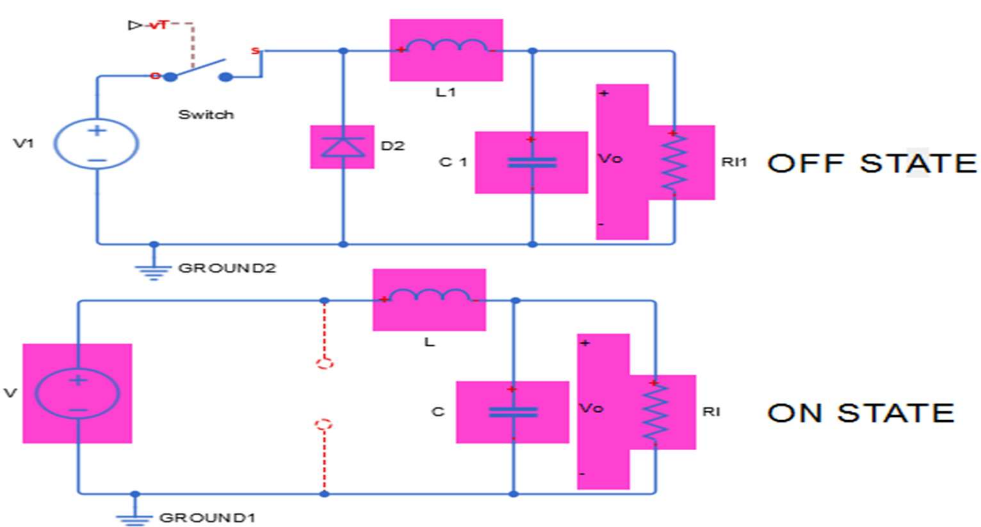


Figure 3: Buck Converter Operation States

Assuming the initial condition of the switch is in the OFF state, the current in the circuit is zero. Now, when the switch is closed for a period equal to the duty cycle, the inductor current will begin to increase and this will lead to a voltage of opposite polarity across the inductor. The source voltage is of opposite polarity to the inductor voltage and the net voltage which is the voltage across the load is reduced. From the general expression that the rate of change of current across an inductor multiplied by the value of the inductor in Henry gives the voltage drop across the inductor, we can see that with time, the rate will decrease and therefore the voltage across the inductor will also decrease in turn which would lead to an increase in the load voltage. During this time, the inductor stores energy in the form of a magnetic field and If the switch is opened while the current is still changing, there will be a voltage drop across the inductor. This shows that the load voltage will always be bucked i.e., lower than the input voltage. When the switch is opened again, the voltage source will be removed from the circuit, and the current will decrease. The changing current lead to a change in voltage across the inductor. The stored energy in the inductor's magnetic field supports current flow through the load. At this time, the inductor is discharging its stored energy into the rest of the circuit. If the switch is closed again before the inductor fully discharges, this is referred to as a continuous operation. If it is allowed to totally discharge, then that is discontinuous mode of operation. The expression

$$Vo = Vin(D) \tag{5}$$

shows the relationship between the input voltage, output voltage and the duty ratio. Note that the magenta colored part of the diagram indicates the parts that are contributing to the output at each state. In Figure 4 below, a schematic of a typical simulation is shown, it was carried out using Simpower in Simulink, a

MOSFET was used as the switch with input voltage of 50V, inductor value of 400µH and a capacitor value of 100µH operating at 20kHz. The size of the inductor also determines if the circuit will work in a continuous or a discontinuous mode and it is continuous in this case. The output voltage is expected to be around 20V based on result obtained using the basic formula for evaluation.

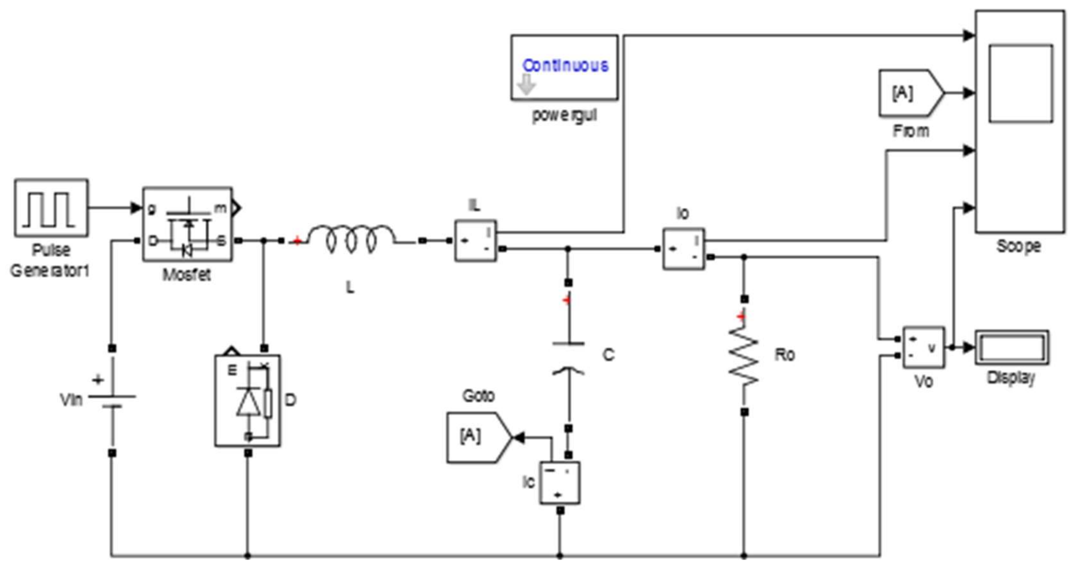


Figure 4: Buck Converter in Simpower

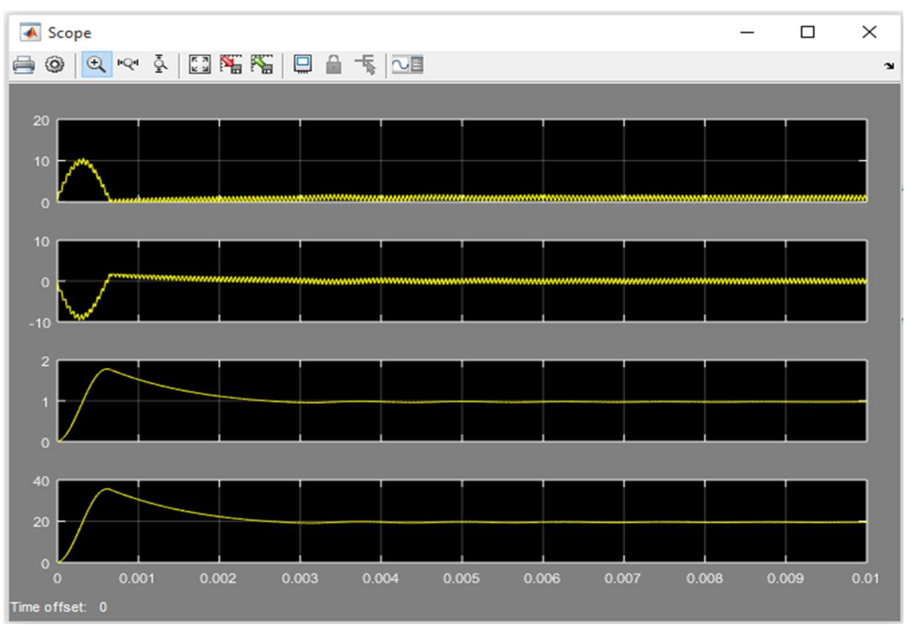


Figure 5: Buck Converter Output in Transient and Steady State

The first segment in the munched scope, Figure 5, shows the inductor current, the second is the current through the capacitor, the third is the load current and the last is the load voltage of about 19.16V. This converter is easy to implement, uses only one switch, cheap, has low noise at output and also gives room for a compact design. However, this can only be operated in a unidirectional manner to help reduce voltages and not boost nor capable of doing both. The converter also doesn’t isolate input from output electrically and therefore poses some safety issues when it comes to utilization as the ground isn’t safe. Another important disadvantage is that it produces a high power loss called the switching loss when operated under a high frequency.

2.2.2 Boost Converter

This is another converted that can be realized by turning on and off of an electronic switch. The circuit arrangement is similar to that of a buck converter with the major difference being the change in the positions of the switch, inductor and diode. In this case, the output voltage is higher than the input voltage, this is the obvious reason behind the name given to the converter. This converter also exhibits most, if not all of the advantages of the buck converter. However, it can only be used in one direction just like the buck, it can also only increase the input voltage by a factor based on the duty ratio but cannot reduce the voltage and of course suffers from switching losses too.

2.2.3 Buck-Boost Converter

This converter is capable of reducing and also decreasing the input voltage. The circuit arrangement looks like the combination of the buck and boost circuit. The operation can also be analyzed in two states which are switch ON and switch OFF states. In Figure 6, a diagram that used colors to show how the switches turn on and off during operation, indicating the difference in the circuit arrangement compared to other topologies was shown. The magenta colored components indicate the active (directly contributing) components in the different states of operation.

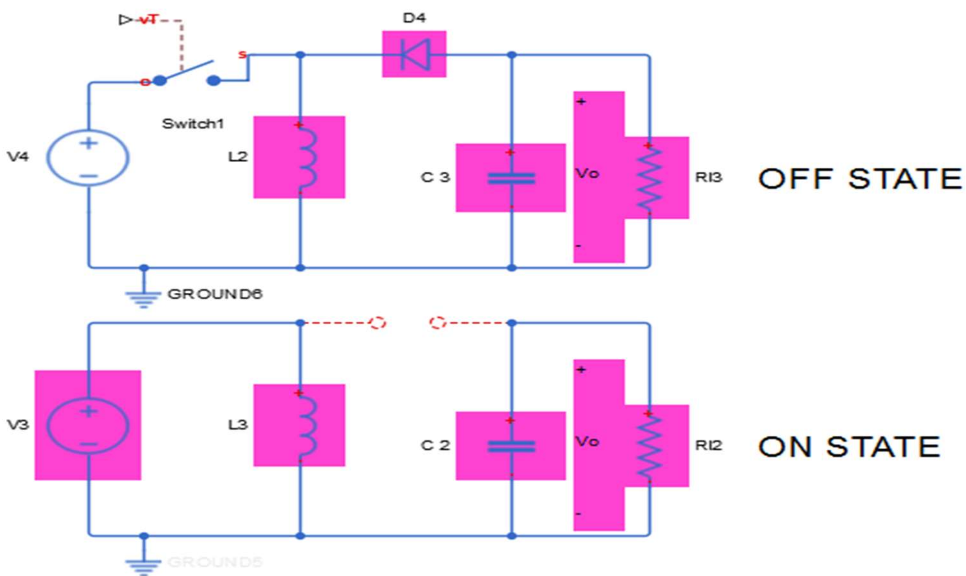


Figure 6: Buck-Boost Operation States

Here, the duty ratio determines the way the converter operates. Simply put, we can assume that the midpoint between buck and boost is 0.5, if this value goes higher, it acts as a boost converter and if it goes lower, it acts as a buck converter. In Figure 7, a typical simulation using Simpower in MATLAB with input voltage of 24V, inductance of 20μH, capacitance of 80μH at 100kHz frequency was carried out to show the behavior of the buck-boost converter when the duty ratio is varied slightly across the boundary, 0.5.

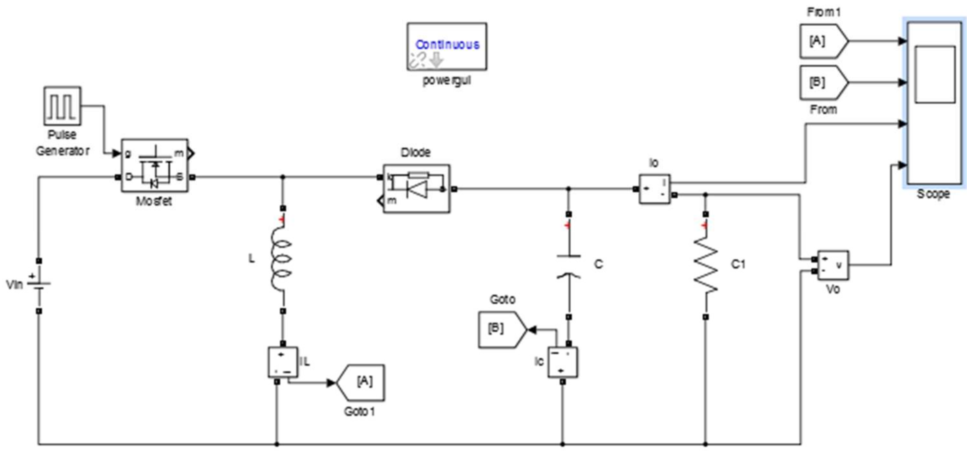


Figure 7: Buck-Boost Converter in Simpower

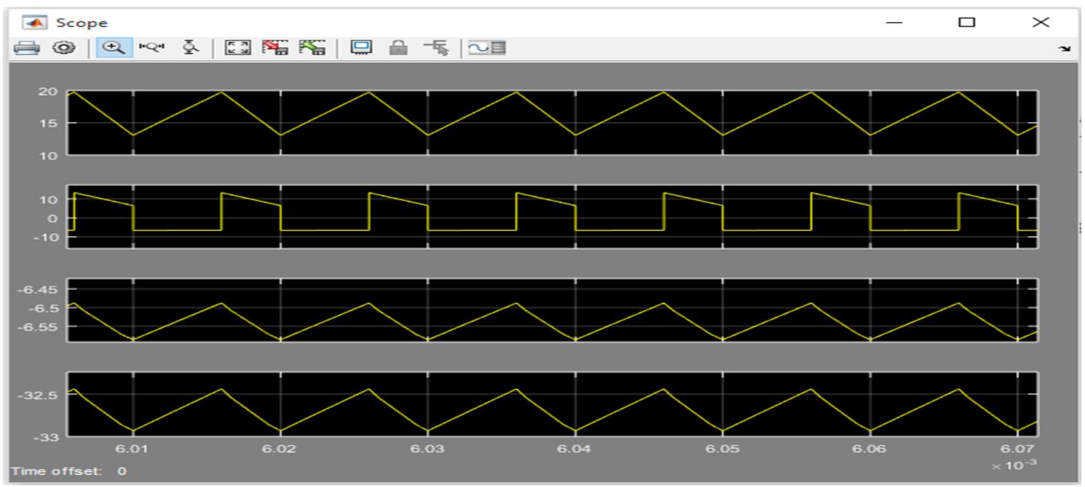


Figure 8: Buck-Boost at 0.6 Duty Cycle in Steady State

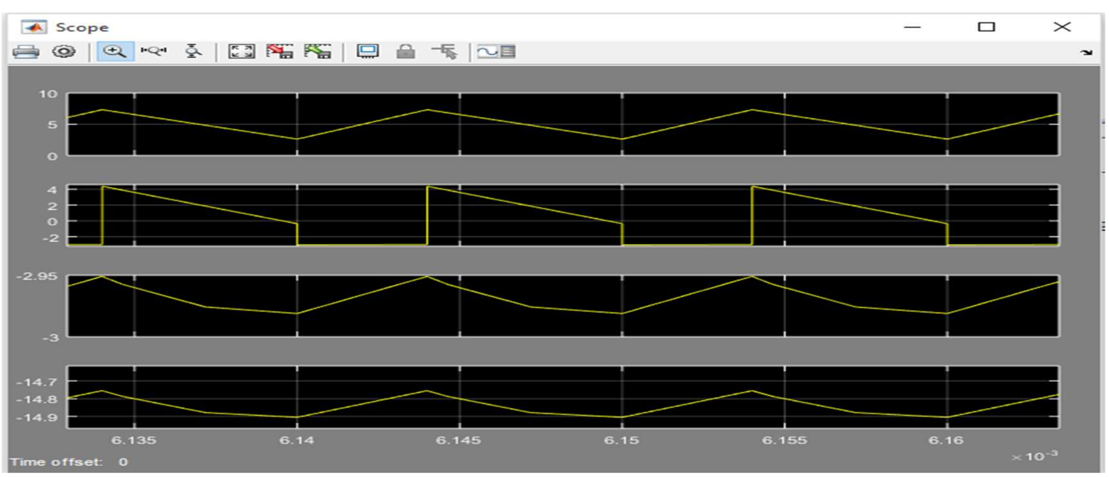


Figure 9: Buck-Boost at 0.4 Duty Cycle in Steady State

In Figure 8 and Figure 9, the boost and buck operation of the buck-boost converter are shown respectively. The first rows in the scopes indicate the inductor currents, second rows, the capacitor currents, third rows show the load currents and the last rows show the load voltage. The expression

$$V_o = -[V_{in}\left(\frac{D}{1-D}\right)] \qquad (6)$$

shows the relationship between the input, output and the duty ratio [5]. We can see that the output voltage at 0.6 duty cycle is about -33V which is more than the input voltage of 24V while the max output voltage when the duty cycle is 0.4 is about 14.9V. This shows how this converter can work to increase and also decrease the input voltage.

Apart from this, this converter is also easy to implement, cheap, and gives room for a compact design. However, this still operates in one direction alone, has high switching loss and gives an output voltage that is of opposite polarity to the input voltage which is shown in the two scopes above.

2.3 Electrically Isolated Converter

Having discussed some of the common DC-DC converters that do not isolate the input source from the output section, we would discuss an existing topology in which there is an electric isolation between the two sides.

2.3.1 Flyback Converter

This is an improved buck-boost converter in which the inductor is being replaced by a transformer. The transformer in this case is like a coupled inductor. We also have other types of transformer isolated DC-DC converters derived from the Buck converter such as Forward, Full and a Half bridge converter. In the normal buck-boost, when the switch is on, the input source forces current into the inductor and raises the stored energy and this energy flows into the load through the diode at the output [1,6]. To avoid energy build-up in the inductor, the average power in the inductor must always be zero, if this is the case and we know it is electrically correct, it makes it more interesting as we can couple the inductor with another inductor, one inductor collects the energy and the second inductor transfers to the output. By doing this, we have been able to electrically isolate the input from the output which is a very important feature of the flyback converter. The transformer with turn's ratio 1/N also helps a great deal in the voltage transformation as a non-unity secondary turns (N>1) would help add a factor to the existing conversion factor which is from the duty ratio as seen in the buck-boost converter. It is called a flyback converter because when the input switch turns off, the inductor output voltage flies back and then the diode turn on occurs. Another important feature of this converter is that the output can be used for both negative and positive voltage applications by simply inverting the output inductor terminals. The flyback converters are mostly used in high voltage and low power applications.

A typical simulation of a flyback converter is shown in Figure 10, the simulation was carried out for a 24V input voltage, 1:1 turn's ratio, magnetizing inductance of 500µH, output filter capacitance of 100µH at a frequency of 100 kHz. Both the buck and the boost properties are also shown in the simulation from the result through the scopes as shown for the ordinary buck-boost converter.

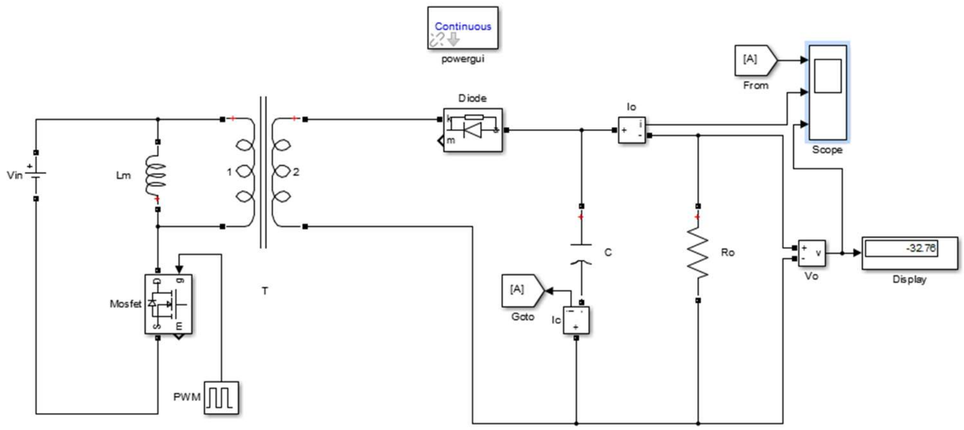


Figure 10: Flyback Converter in Simpower

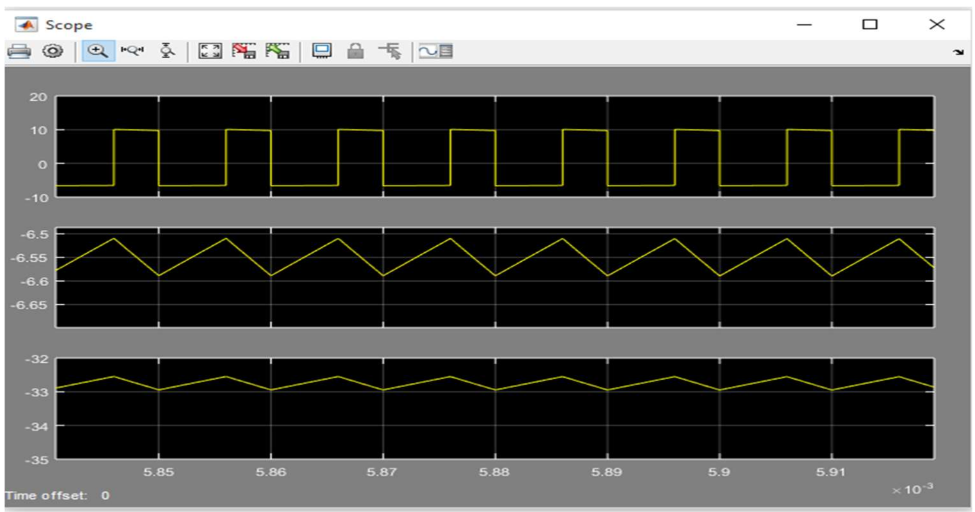


Figure 11: Flyback Converter at 0.6 Duty Cycle in Steady State

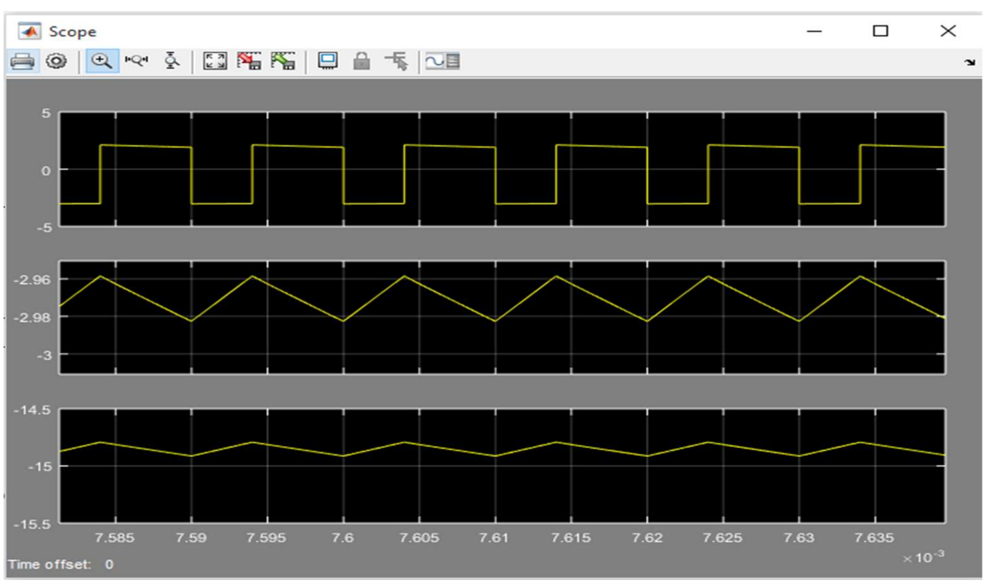


Figure 12: Flyback Converter at 0.4 Duty Cycle Steady State

The first rows in the scopes in Figure 11 and Figure 12 above show the current through the output capacitors, the second rows show the load current and the third rows show the load voltage. In addition to the safety from shock hazards that this converter ensures through isolation from the input, it helps to achieve different reference potentials when needed, it also helps to avoid using large semiconductor devices by using transformers to switch between voltage levels.

2.3.2 Single Active Bridge

This is an isolated DC-DC converter that was developed in the process of trying to achieve a more efficient means of converting DC voltage from one level to another to help better harness renewable energies. This topology helps not only in the efficiency aspect but also in achieving safer designs by electrically isolating the input from the output [7]. It contains four active switches on the input side before the transformer that operates relatively similar to the way inverter switches operate, four diodes at the output section after the transformer that also operates in the same format as a passive full-bridge rectifier's diode operation. Another important device is the transformer that provides the isolation mentioned above and helps in the flexibility of the output by its step-up or step-down capability [7].

Overall, the output can be varied by using the duty-ratio of the active switches, the phase shift value and of course, the transformer [7]. This design and a number of subsequent designs belong to the family of resonant converters, however, the major (most obvious) drawbacks in this design are the unidirectional nature of the DC-DC converter and also the inability to vary the output frequency which might be needed in some applications such as variable speeds in motor controls and possible elimination of a variable frequency drive (VFD). The schematic of a sample simulation and outputs of a Single-Active Bridge in SimElectronics (Simscape) that can be controlled using the duty ratio are shown in Figure 13, Figure 14, and Figure 15 respectively. The switches operate at 20kHz with an input Voltage of 600V. MOSFET switches were used and the transformer turns ratio is one to one.

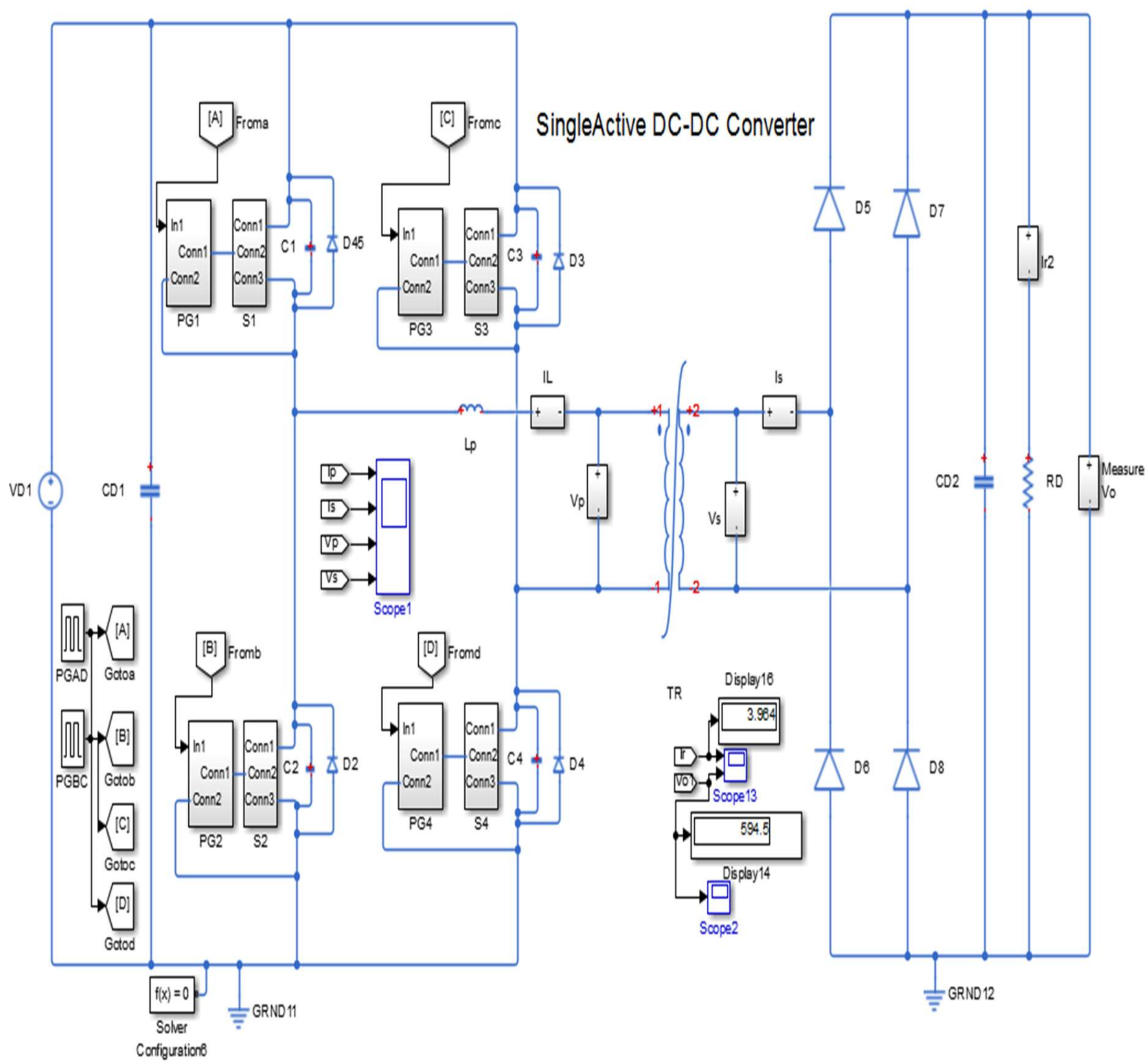


Figure 13: Single Active DC-DC Converter with 0.5 Duty Cycle

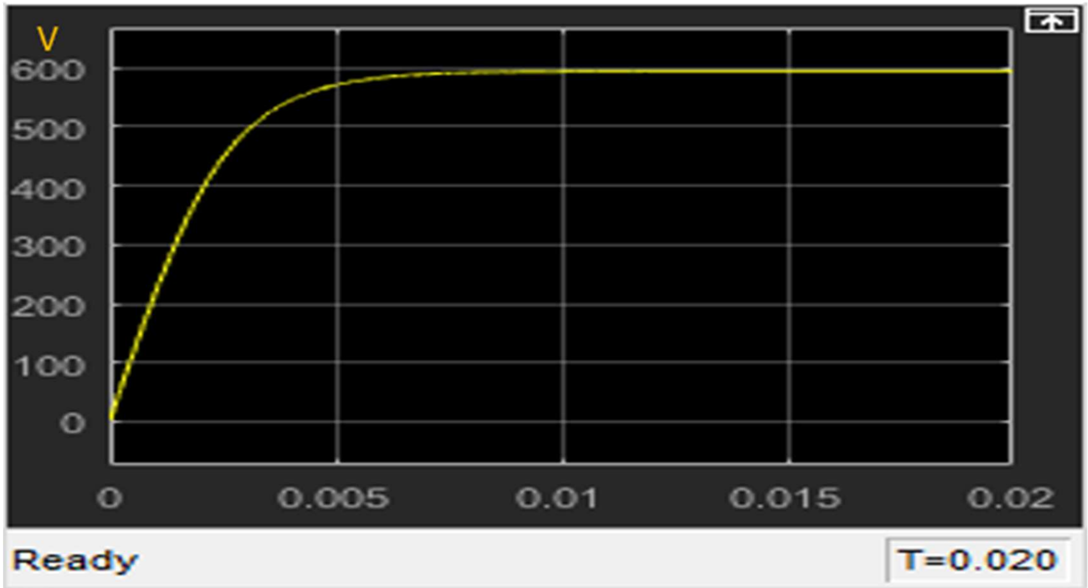


Figure 14: Output Voltage of Single Active DC-DC Converter

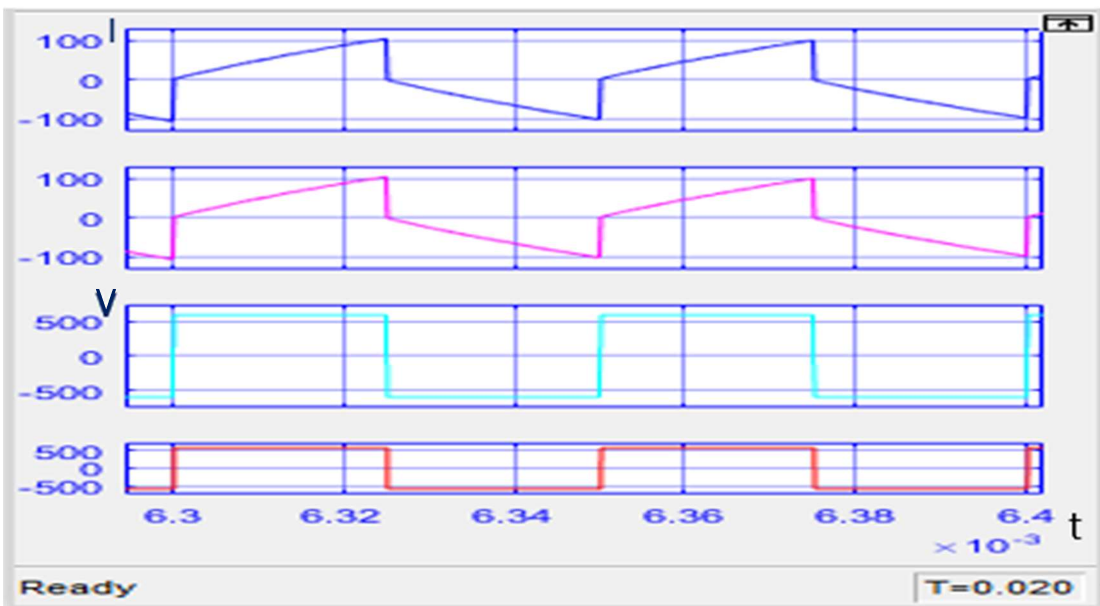


Figure 15: Transformer I and V of Single Active DC-DC Converter

The first two rows in Figure 15 represent the primary and secondary currents while the last two rows represent the primary and secondary voltage of the transformer in the Single Active Bridge Converter. AC power is obtained at this stage due to the first (input) H-Bridges operating as an Inverter.

CHAPTER 3 PROPOSED TOPOLOGY

The topology as stated earlier is a medium Voltage Cascaded Multi-Level Converter with Isolated High Frequency Links to improve efficiency in harnessing renewable energies. The power module to be cascaded in this context is a combination of three converters namely, the Full Bridge Rectifier, an isolated DC-DC converter, and the Active Inverter. These three converters were made bidirectional, thereby, making each module bidirectional as well.

There are four basic stages involved in achieving the design of this cascaded multi-level converter, with each stage contributing to the efficiency, miniaturization and overall performance of the system in harnessing renewable energies using SiC switching devices in the DC-DC converter section. These stages are interdependent on each other, making an improvement on one of the stages have an appreciable positive effect on the whole system. Below are the four stages involved in the converter system;

The Grid conversion stage: Depending on the output from the renewable energy collector, this stage handles the conversion of the raw power from the Grid to a usable DC by using a rectifier or a DC-DC converter respectively.

DC-DC Conversion: At this stage, the DC power from the rectifier stage will go through an internal double conversion process, depending on the load size, type and also the transmission distance. There are various methods one can adopt when it comes to DC-DC conversion, some of which were discussed earlier. Others that were not discussed are CUK, SEPIC, forward converter, etc. Here, we are using a DC-DC conversion in which there is an isolation between the input and output- A Bidirectional Dual Active Bridge (BDAB) Converter. The main idea behind converting to DC, knowing it would be converted back to AC for usage, is because of the need for a cleaner DC power, HVDC compatibility (in situations where the renewable energy collector is in a remote area due to geographical or aesthetic reasons) and the more control and safety options presented by using the BDUAB.

DC-AC conversion (Load conversion stage): This is the stage where the final conversion takes place and this can be achieved by an Inverter to supply the AC load which could be a motor, or other compactible industrial loads. A Bidirectional active inverter is used in this case in order not to jeopardize the intended bidirectional nature of the system.

Cascaded Module: This stage involves the physical cascading of a number of modules in series to make a phase with the required voltage and phase shifting three different strings as necessary to achieve the desired number of phases. The stages described above can be diagrammatically shown below in Figure 16.

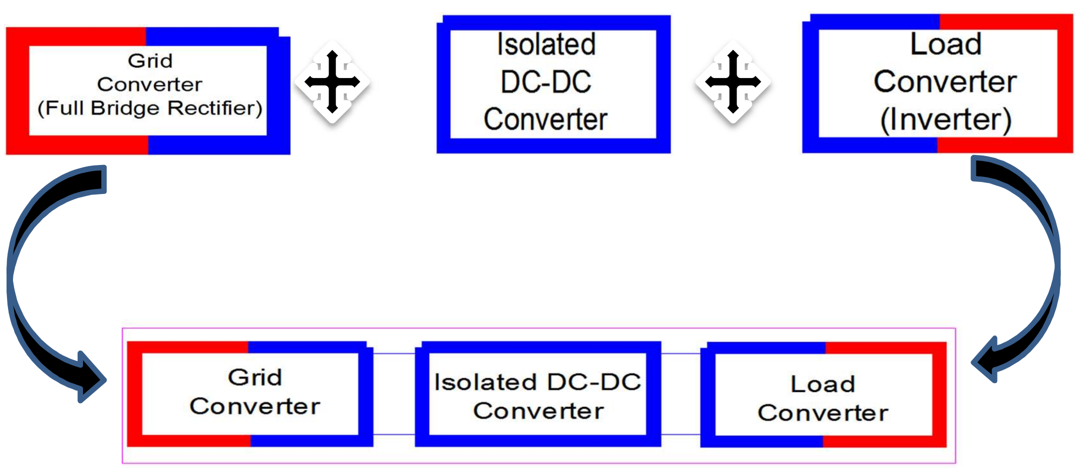


Figure 16: Module Formation

3.1 Full-Bridge Active Rectifier

This can be referred to as the input converter in the module. It could sometimes be optional based on the nature of the energy source and the energy collector interacting directly with the source. For example, solar panels are used for solar energy, wind turbines for wind energy, steam turbine for geothermal energy etc., the first produces DC power while the second and third produces AC power [1,3]. There are different ways of achieving this voltage rectification but we chose a full bridge rectification in order to avoid unnecessary ripples in the output or reducing the power density by large filtering capacitors.

Based on the voltage level of the circuit and its application, despite being able to reduce the ripple, there is a systemic need for a bidirectional module and this leads to the use of active switches in place of the conventional diodes in a full bridge rectifier. In the forward direction, it works as a rectifier and in the reverse direction, it works as an inverter. We have a reasonable level of simplicity when it comes to switch selection as the frequency of the source (60Hz) is the switching frequency of the switches, therefore, there is no consideration for high frequency switching and we can use either a MOSFET or IGBT for the simulation process. The function of the converter depends on where the input is fed into and where the load is connected on the full-bridge as shown below. As indicated in Figure 17, when an AC voltage is supplied from the left hand-side in a typical full-bridge converter set-up, the output at the right-hand side is a DC output, provided the switches are well coordinated. On the other hand, when a DC voltage is supplied from the right-hand side and the switches are rightly coordinated, the output at the left-hand side is an AC output.

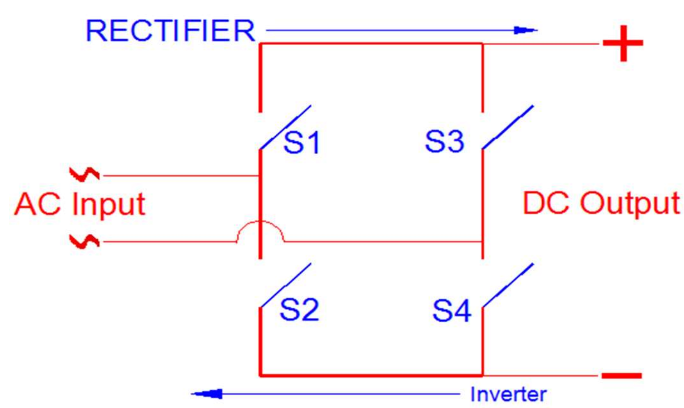


Figure 17: Rectifier Schematic.

3.2 Full-Bridge Active Inverter.

This converter is the output converter used to converter DC voltages to an alternating voltage. The DC input could be a pure DC or a pulsating DC (with ripples but not changing signs), depending on the nature of the source [1,3]. In this case, the DC input is a pulsating type due to the fact that it must have gone through the DC-DC converter, whose output cannot practically be a pure DC. The schematic is shown in Figure 23 below.

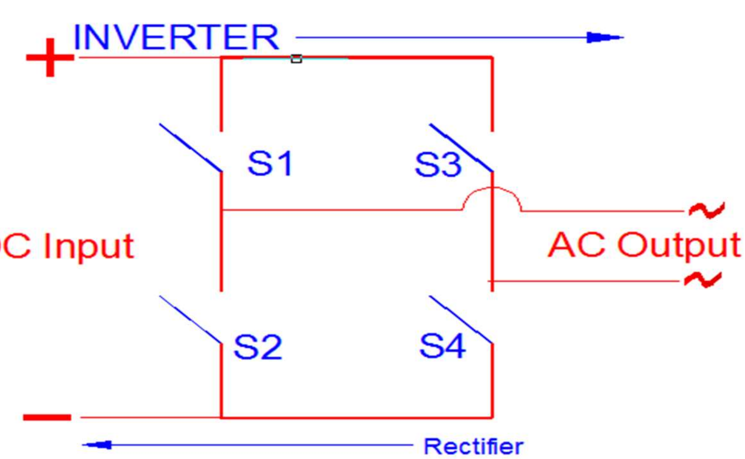


Figure 18: Inverter Schematic.

3.3 Isolated DC-DC Converter

This is the second portion of the module discussed earlier. The topology to be adopted is the first thing to decide when choosing a converter for a system. The decision is a function of a number of factors, some of which are:

1. Cost of production.
2. Simplicity.
3. Power rating.
4. Flexibility in design (uni-directional or bi-directional operation and compatibility with other systems).
5. Input and output voltage range.
6. Safety consideration (electrically isolated or non-isolated converter).
7. Power density consideration.

In the cascaded topology proposed here, the Full Bridge Bi-directional Dual-active Converter was used. This choice is based on factors such as its high frequency operation, high power density, bi-directional operation, electrical isolation from the source through the transformer, as well as buck and boost operation compatibility by duty ratio variation [7]. As seen above, these qualities make it a great choice, considering the decision making factors mentioned above. Apart from its basic application in DC-DC conversion systems, it has applications in DC-AC (inverters), AC-AC (frequency and magnitude regulators), AC-DC (rectifiers) and in Hybrid Electric Vehicles (HEVs) [9]. The mentioned area of applications are very important and popular in the world of power electronics as a whole and power electronics dependent areas as well.

3.3.1 Bi-directional Dual Active Bridge

The Bi-directional Dual Active Bridge Converter (BDAB) contains eight active switches, four of which make up the input bridge section before the transformer and the other four make up the output bridge after the transformer. Apart from the switches, the BDAB usually contains a high frequency link transformer which can be used to boost the voltage level, depending on the application and which also brings in the galvanic/electrical isolation of the system. The duty ratio of the switches, D, is the ratio of the time in which the switches are ON to the total period, T [7,8,9]. It is expressed as

$$D = Ton/(Ton + Toff) \qquad (7)$$

and

$$D = Ton/T = Ton \cdot f. \qquad (8)$$

It ranges from 0 to 0.5 for the BDAB and it is varied to help vary the output voltage, in which a 100% means 0.5 and a 0% means a 0. This mathematically means for every 1% increase needed, the duty ratio should be made to increase by approximately 0.005 between 0 and 0.5.

The bi-directional nature of the BDAB is achieved by using the phase shift between the input bridge and the output bridge. This is analogous to the normal power flow equation given as

$$P = (V_1 \cdot V_2 \cdot sin\, \alpha)/X, \qquad (9)$$

where $\alpha =$ phase shift and X is the impedance.

There is a forward power flow when $\alpha > 0$, and a reverse power flow when $\alpha < 0$. Figure 22 shows a pictorial representation of the bidirectional feature.

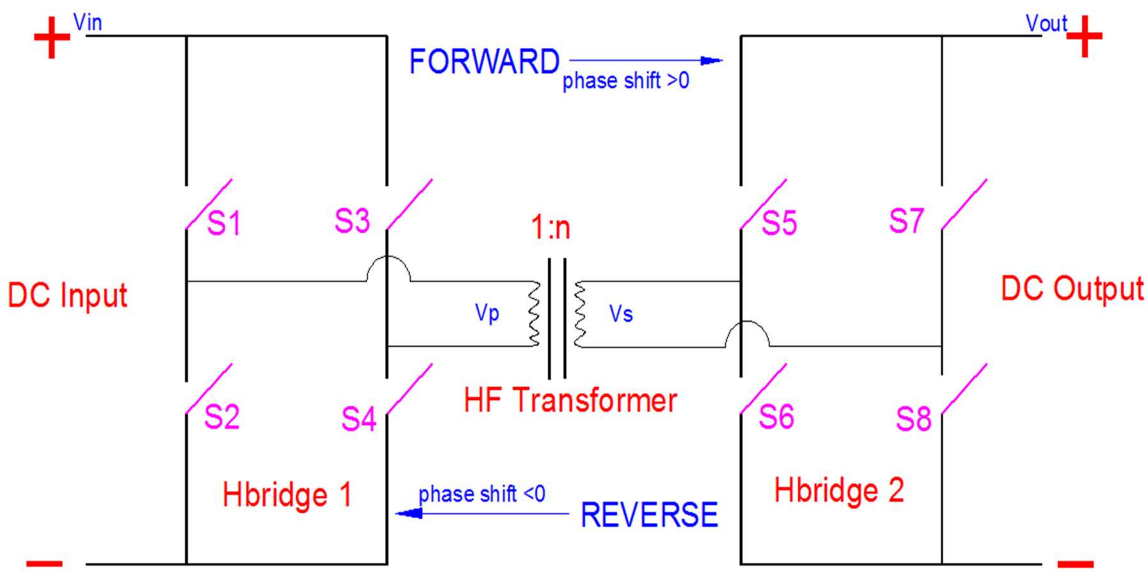


Figure 19: Bi-directional Dual Active Bridge

In addition to the duty ratio, the output voltage is also dependent on the turn's ratio of the high frequency transformer (HFT). In this case, it was assumed that the HFT is ideal with a 1:1 turn's ratio, i.e., N is 1. The switching topology with 50% duty ratio is shown in Table 1.

Table 1: Switching States for BDAB

s \ t	$0\ to\ \alpha$	$\alpha\ to\ \left(\frac{T}{2}\right)$	$\left(\frac{T}{2}\right)$ to $\left(\left(\frac{T}{2}\right)+\alpha\right)$	$\left(\left(\frac{T}{2}\right)+\alpha\right)$ to T
S1	On	On	Off	Off
S2	Off	Off	On	On
S3	Off	Off	On	On
S4	On	On	Off	Off
S5	Off	On	On	Off
S6	On	Off	Off	On
S7	On	Off	Off	On
S8	Off	On	On	Off

Implementing the switches as shown above, the transformer primary and secondary voltages are a two-level AC voltage related by the equation,

$$V_p = V_s(1/N). \tag{10}$$

At 50% duty ration, the input and output voltage can also be linked in the same way as

$$V_{in} = V_{out} \cdot (1/N). \tag{11}$$

The phase shift variation mentioned above, used for varying the direction of power flow and sometimes, the voltage magnitude is α , as indicated in the table above. The negative sign (<0) of the phase shift for the reverse operation of the converter can be thought of as simply swapping the switching operation of the input bridge switches with the output bridge switches [9,10,11].

3.4 Power Converter Module

This is the combination of the three converters described above. It is bi-directional in nature due to the bi-directional nature of the individual converters. The module retains the controllability of the individual converters by using the phase shift and duty ratio in the Bi-directional Dual Active Bridge. The Inverter at the output stage also helps in varying the frequency and nature of the output AC voltage. In this case, the output voltage would be a multi-level voltage by varying the phase shift and duty ratio of the Inverters in a series connected module. The module is shown in Figure 23 with the terminals of the converters left unconnected in order to make readily obvious, the terminals to be connected, retaining the schematics for the individual converters.

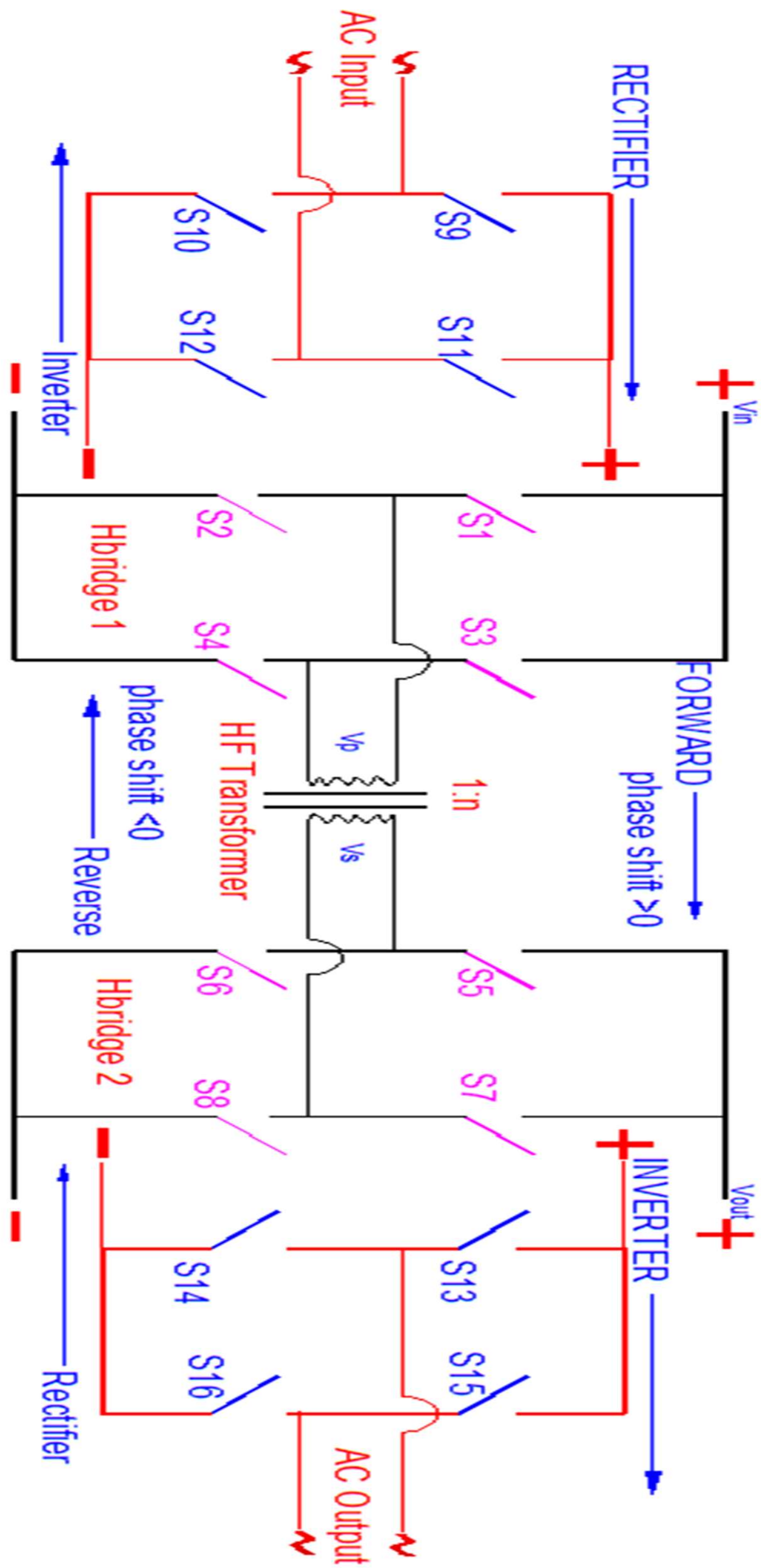


Figure 20: Power Module Schematic

3.5 Cascaded Converter

The cascaded system is a combination of the power modules discussed above in series and parallel. The series combination is the equivalent series connection of 4 modules, thereby, increasing the voltage level of the system. The multi-level final output is achieved by introducing phase shifts to the Inverter section of the modules. These multi-level cascaded power converter has advantages such as high power compatibility, low switching losses, low concerns for electromagnetic compatibility and high power quality. To obtain the three phase system, three legs (each leg/string contains 4 modules in series) are Y-connected and phase shifts are introduced. This result in the over-all cascaded power converter with the direct ability to increase the current rating and power.

An important aspect in this section is the switching and the delay introduced in order to achieve the multi-level output. Each outermost converter (inverter) has 4 switches as described earlier, diagonal switches on each of them operate at the same switching frequencies and delay. The reduction in the duty ratio as we move from one module to another helps in achieving a step-like signal [12]. Three different output frequencies were considered as shown in

. The percentage is given in terms of the period and the other half is the negative half cycle- a mirror image of the first. The pulse width percentage can be varied based on the required output; the lowest pulse width could be 10% in some cases [12,13]. The pulse width is a function the designer and can be varied differently provided the delays are even and corresponds to the second half-cycle.

Table 2 : Switching Scenarios for BDAB

SWITCH	PULSE WIDTH % OF T	30Hz SCENARIO		60Hz SCENARIO		120Hz SCENARIO	
		Period	Delay	Period	Delay	Period	Delay
I1a	40%	1/30	1.667E-3	1/60	8.333E-4	1/120	4.167E-4
I1b	40%	1/30	1.833E-2	1/60	9.167E-3	1/120	4.583E-3
I2a	30%	1/30	3.33E-3	1/60	1.667E-3	1/120	8.333E-4
I2b	30%	1/30	2E-2	1/60	1E-2	1/120	5E-3
I3a	20%	1/30	5E-3	1/60	2.5E-3	1/120	1.25E-3
I3b	20%	1/30	2.167E-2	1/60	1.083E-2	1/120	5.417E-3
I4a	10%	1/30	6.67E-3	1/60	3.333E-3	1/120	1.667E-3
I4b	10%	1/30	2.33E-2	1/60	1.167E-2	1/120	5.833E-3

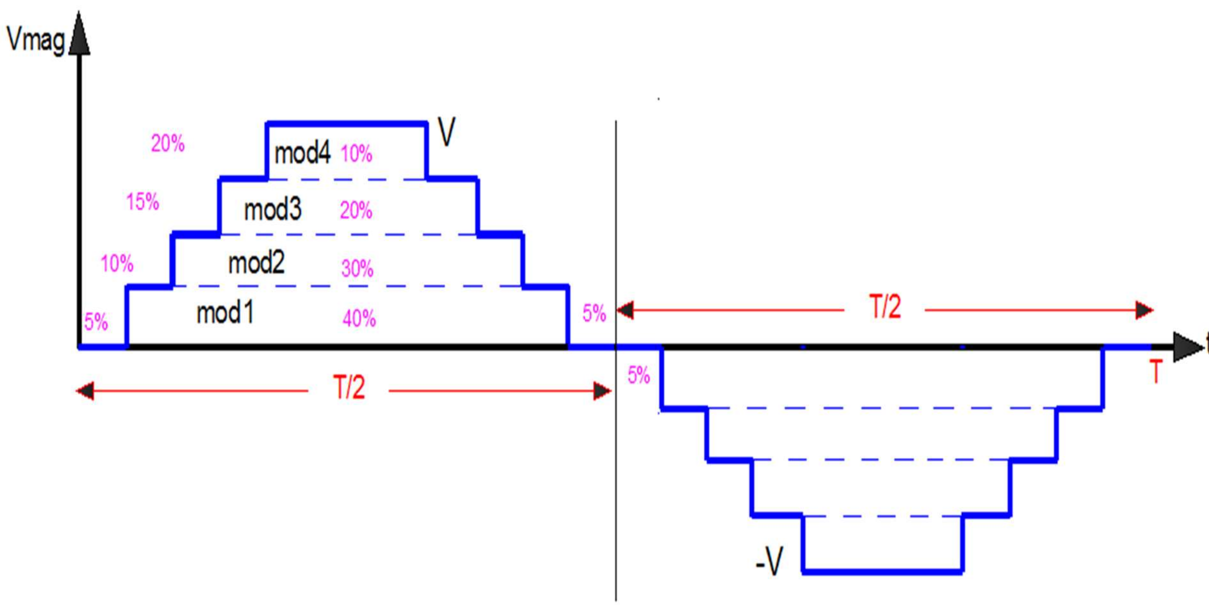


Figure 21 : Bi-directional Dual Active Bridge [13] [14]

Let's say "N" is the number of Converters in series, number of levels in multi-level output is 2(N)+1 and this includes both half cycles. The phase shifts of the positive half-cycle of each diagonal pair of switches is $T/2$ less than the phase shift of its corresponding negative half-cycle paired switches [14].

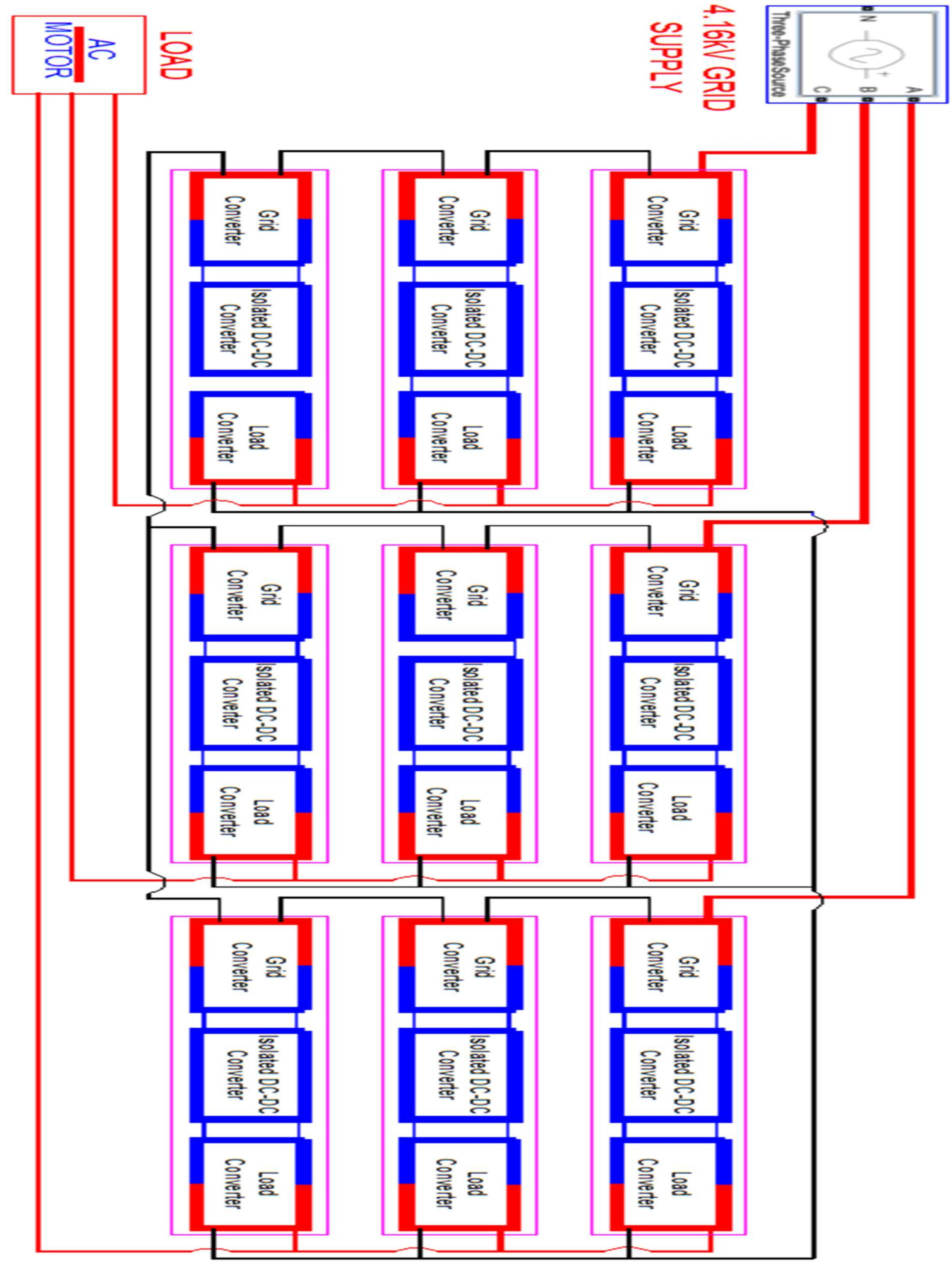


Figure 22 : Cascaded Module Formation

Figure 22 above shows the schematic of the cascaded topology with the black and red color being used to show the ground and the phases respectively. The arcs are used to show a non-intersection of connection lines and the modules can be changed to more or less than 3 modules in series, depending on the required voltage and voltage rating of the switching devices. The different converters that make up each module, the cascade topology, and the switching of the semiconductor devices will be discussed in detail. Each module is designed for an input of 600V and a maximum ripple of 0.083%. A very important contributor to the efficiency increase in this topology is the switching devices adopted. Based on the high frequency switching in the DC-DC converter, the SiC switch was used but based on cost consideration and low frequency operation, the normal MOSFET or IGBT can be used in the rectifier and the inverter section.

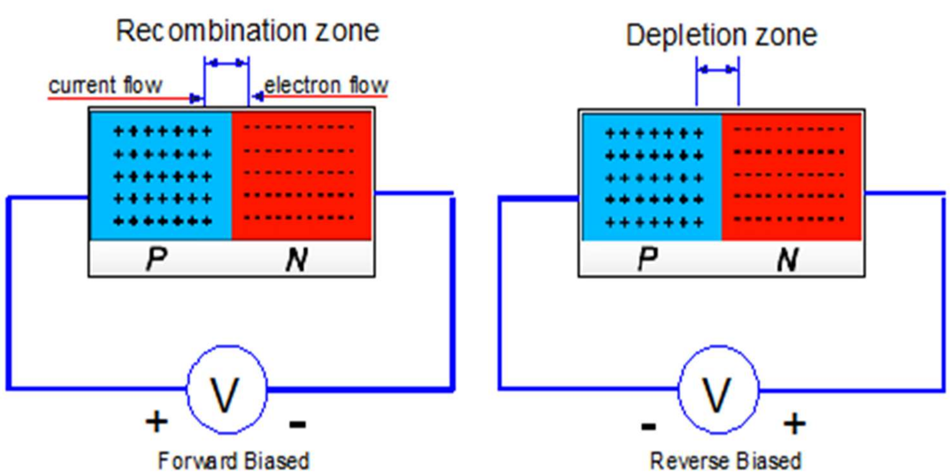
CHAPTER 4 MODELING OF SWITCHING DEVICE

For years, silicon (Si)-based power/semiconductor devices have dominated the power electronics world when it comes to selection of switching devices. However, these devices' limitation in functionality has become more pronounced, basically due to the inherent nature of the material (silicon) in question [2]. The more complex auxiliary power system designs become, the less efficient and effective the Silicon devices become in their application. The three most common features that require constant upgrade along with technological advancement are high frequency, high voltage and high power density.

A typical example is silicon metal-oxide-semiconductor field effect transistors (MOSFETs), the device is ideal for high frequency switching up to MHz with minimal switching losses but it has a high on-state resistance which leads to a high conduction loss. This limits the application to medium voltages except when the voltage drop is of no importance [2]. The Silicon Insulated-gate bipolar transistors (IGBT) are capable of handling high voltage and current but under low switching frequencies below 100kHz [2,15]. The converters built with these devices are based on the ability to strike a balance between high voltage and high frequency, in order words, it is based on the ability to strike a balance between the power rating and power density. These devices are presently the most widely used semiconductor material for power devices, but as discussed above, their material limits have triggered lots of research works to fine alternatives to achieve better functionality. The research work has led to the development of some wide band gap switches such as gallium nitride (GaN), and silicon-carbide (SiC) switching devices. They have evolved from just laboratory prototypes to industrially marketed devices, thanks to organizations such as Cree Inc., Powerex, Infineon etc. When compared to Si devices, the cost is higher, but these wide band gap devices are steadily being adopted in applications that can enable the manufacturers tap into the many benefits of the technology and therefore offsetting the increased cost factor. The SiC MOSFET is a voltage controlled semiconductor device that act as a current source or controls the flow of current. Based on the type of doping technique, it could be an n-channel or a p-channel MOSFET. The n-channel is the most popular in switching circuits due to its lower on-resistance when compared to the p-channel MOSFETs. The manufacture and operation has its roots from the way diodes are manufactured, which is by joining two differently doped materials (p and n) to obtain a p-n junction diode. A quick review of diodes, I/V characteristics and how they work in both forward and reverse biased modes is very important as this gives a better understanding of how MOSFETs operate [15,16].

4.1 Diodes

It is very important we review the foundation of the application of semiconductor devices-diodes. A diode, which is the simplest electronic switch, is a semiconductor device that allows the flow of current in one direction (forward bias) and oppose the flow in the reverse direction (reverse bias). In the forward direction, it acts as a conductor with low resistance depending on the material while in the reverse direction, it acts as an infinite resistance. It is usually referred to as a p-n junction material where the type-p is a doped semiconductor material with an abundance of positive carriers (holes) while type-n has an abundance of negative carriers (electrons) [15,16]. A positive voltage applied to the p-section creates a higher concentration of holes and a negative voltage applied to the n-section creates a higher concentration of electrons, when this happens, there is a recombination of electrons and holes at the middle, which means a flow of current. The current flow is basically a function of density gradient between electrons and holes. On the other hand, when a negative voltage is applied to the p-section (electron is fed into the p-section) and a positive voltage to the n-section (holes are fed into the n-section), a depletion zone that contains no free charges is created at the middle and this means no current flows through it [16]. However, all diodes have a maximum reverse voltage (rated voltage) it can withstand. If the rated voltage is exceeded, the diode will fail and start to conduct a large current in reverse direction, this condition is known as the breakdown [16]. Below, is a pictorial description of the way the doped sections work in a forward or reverse direction.



(a) (b)

Figure 23 : (a) Forward Bias (b) Reverse Bias [16]

The diagrams in Figure 24(a) and 24(b) below show the symbol and describes the modes and characteristics for better understanding.

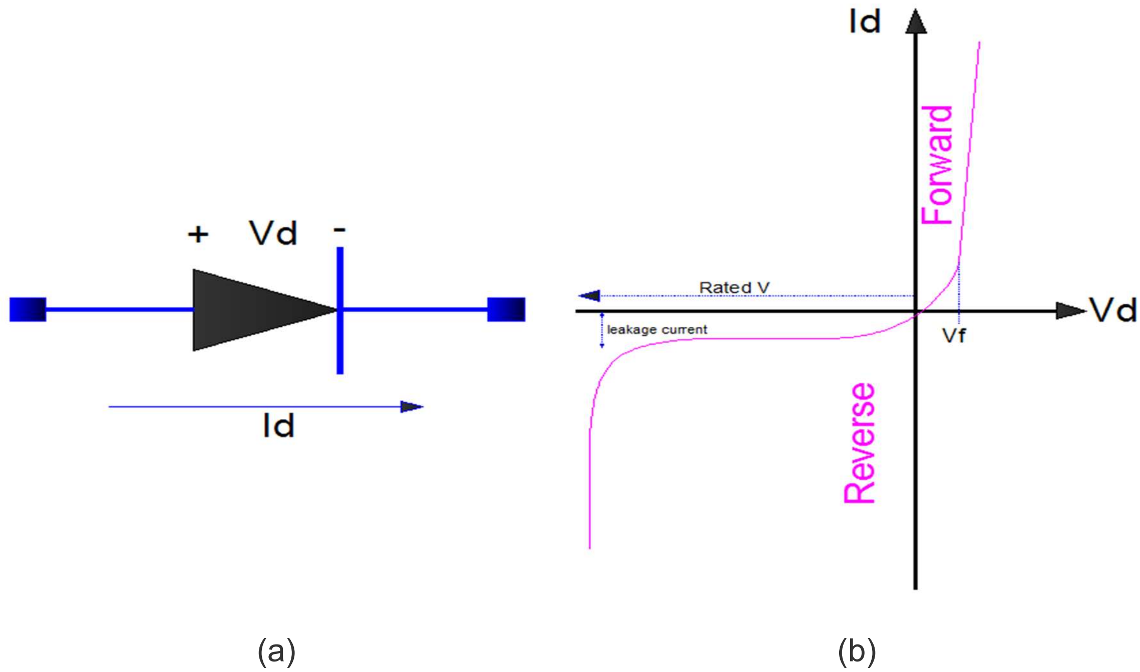
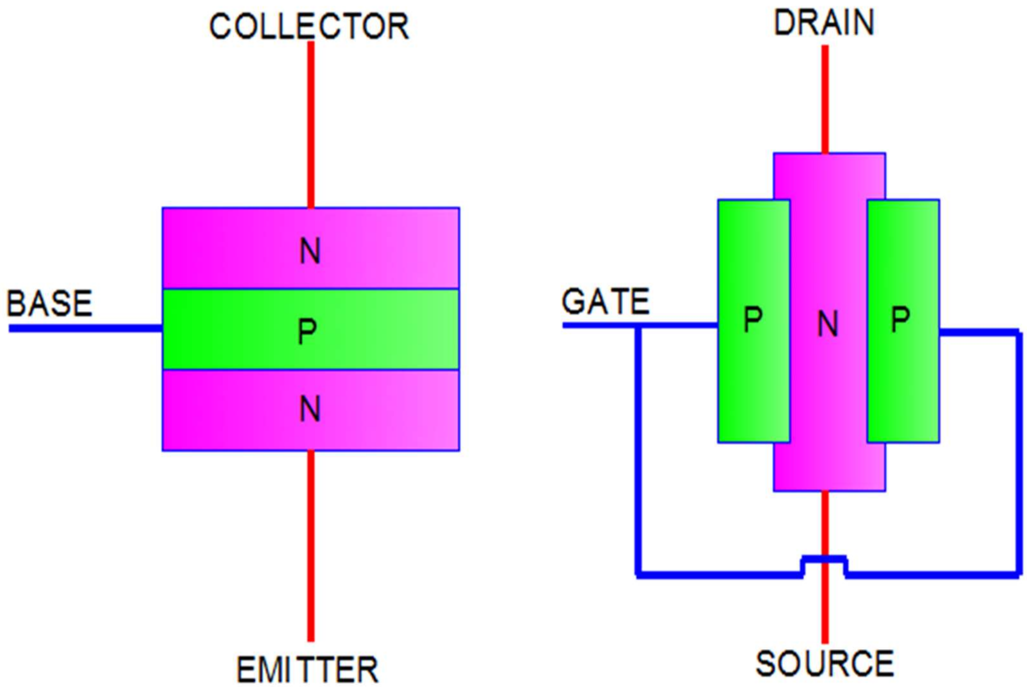


Figure 24 : (a) Diode Symbol (b) Diode I/V Characteristics

4.2 N-channel MOSFETs

Having gone through the foundation of doping semiconductor devices, biasing and diodes which is an important factor in developing the present day switching devices, it is also important to briefly discuss n-channel MOSFETs generally so as to have an idea of its operation before we delve into SiC n-channel MOSFETs, the adopted switch in this topology.

A metal oxide semiconductor field effect transistor (MOSFET) as mentioned above, is a voltage controlled device that is used to control the flow of current. Unlike, the bipolar junction transistors (BJTs), the drive (gate) and the current path terminals are connected differently in MOSFETs. Figure 25(a) and 25(b) show the difference between the method of connection as discussed [16].

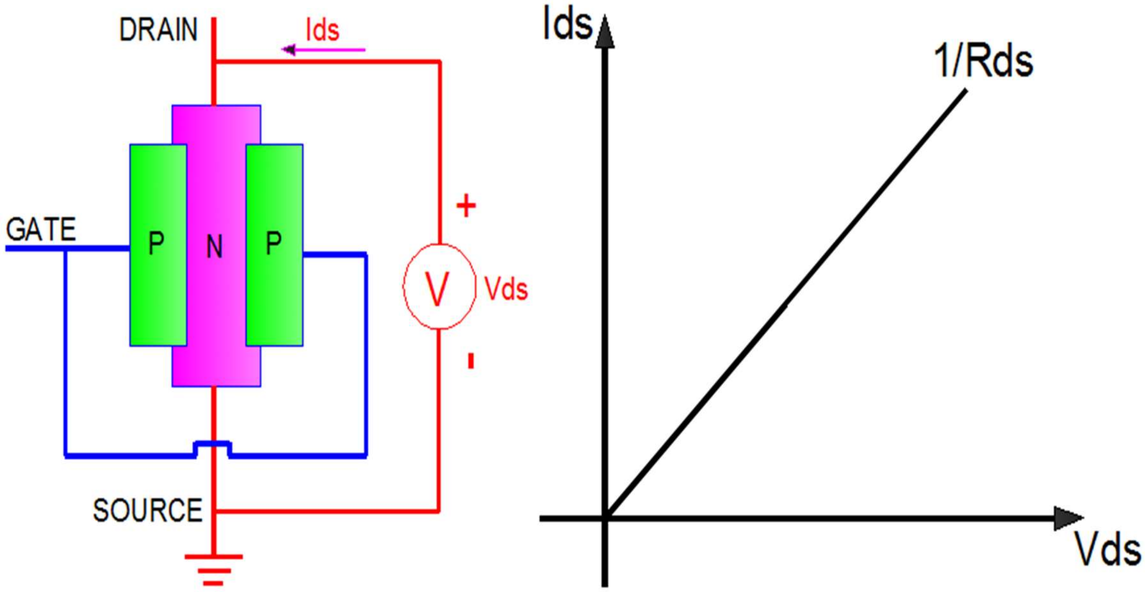


(a) (b)

Figure 25 : (a) N-P-N BJT (b) N-Channel MOSFET [16]

Switching speed and power loss are two very important factor to consider when selecting switches in power electronics. Most electronic circuits that require a relatively swift turn-on and turn-off use MOSFETs based on the fact that they are majority carriers and have no minority carrier storage delays, unlike the BJTs that are minority carrier devices.

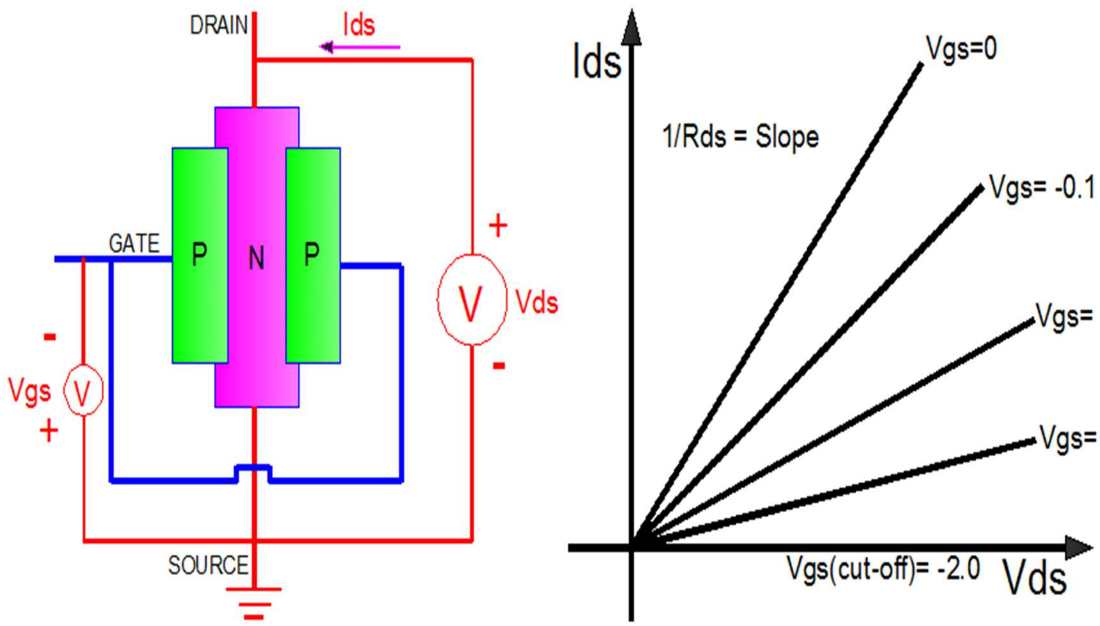
The n-channel MOSFET shown in Figure 25(b) above are mostly used in electronic circuits. The drain and source are analogous to the electron collector and electron emitter in a BJT respectively. Due to the fact that current flows in opposite direction to electron flow, when a voltage source is connected across the drain and the source through the n-channel, current flows from the drain to the source.



(a) (b)

Figure 26: (a) N-channel MOSFET (b) I_{ds} and V_{ds} Relationship [16]

The current, Ids in Figure 26 is a function of the voltage, V_{ds} and the inverse of the slope is the resistance of the channel. A variable resistor between the drain and the source can be created by applying a negative gate voltage and connecting the positive end to the source, this means, as explained above, that we are reverse biasing the p-n junction on both sides. This creates a depletion zone in the channel, narrowing the channel (increasing the resistance), the more negative voltage applied, the narrower the channel becomes. A point is reached when an increase in the negative voltage reaches a value, VGS_{off} and result in a complete cut off of the channel, acting as an infinite resistance. To obtain this cut-off mode, in which there is no current flow through the channel i.e. I_{ds} is zero, a voltage that is less than (more negative) or equal to the VGS_{off} must be applied. Figure 27 shows the relationship between the drain-source current, voltage, and the channel resistance depending on the gate voltage applied [2,16].



(a) (b)

Figure 27 : (a) MOSFET Connection (b) I_{ds}, V_{ds}, R_{ds} V_{gs} Relationship [16]

4.2.1 N-Channel MOSFETs' Operation Modes

There are three modes in which the MOSFETs operate. The choice of operating modes is a function of its application- it could be used as an amplifier and also as a switch, the latter is our area of application and so the necessary mode should be adopted.

The cut-off mode: This is the condition of a MOSFET described above when there is no current flow from the drain to the source due to the depletion layer build up and total pinching off of the current path. It is a mode that mostly describes an OFF condition and it is useful in the other two modes. The mathematical conditions are stated as follows:

$$Vgs \leq \left(Vgs_{cut-off} = Vgs_{off}\right) \qquad (12)$$

and

$$Ids = 0. \qquad (13)$$

Linear/Triode Mode: In this condition, the gate source voltage is greater than the cut-off voltage. When this happens, there is a current flow from the drain to the source and the magnitude of the current is a function of both the gate-source voltage (Vgs) and the voltage source connected between the drain and source (Vds). The higher the Vds, the higher the current flow. An important feature of this condition is the fact that the depletion layer close to the drain is wider that the depletion layer formed close to the source, forming a conical kind of shape. The difference between Vgs and Vgs_{off} is referred to as the over-drive voltage, Vov. In this mode, the voltage across the drain and the source should be less than the over-drive voltage and the conditions are given as follows:

$$Vgs > \ Vgs_{cut-off}, \qquad (14)$$

$$Vgs - \ Vgs_{cut-of} \ = Vov, \qquad (15)$$

$$Vds < Vov\ , \qquad (16)$$

and

$$I_{ds} = K_n \cdot V_{ds}\left(V_{ov} - \left(\frac{V_{ds}}{2}\right)\right), \qquad (17)$$

where K_n is a constant that depends on the material of the MOSFET device.

For MOSFEts to be utilized as a switch (turning ON and OFF at a specified frequency), the parameters should be set to suit the linear or triode mode of operation. In summary, it turns ON in the linear mode, making the channel behave as a variable resistor and turns OFF in the cut-off/pinch-off mode, with the channel behaving as an infinite resistor.

Saturation Mode: This is a condition in which a further increase in Vds from Vds in the triode mode do not translate into an increase in the current flowing through the drain and the source. In this condition, current, Ids is constant irrespective of the voltage (Vds) [16,17]. The mathematical conditions are stated as follows:

$$Vgs > Vgs_{cut-of} \ , \tag{18}$$

$$Vgs - Vgs_{cut-of} \ = Vov, \tag{19}$$

and

$$Vds \geq Vov. \tag{20}$$

Due to the independent nature of the current with regards to Vds, MOSFETs in this mode (ensuring the parameters are set with respect to the conditions stated above) work as an amplifier. The current depends on Vgs and can be shown with the quadratic relationship given as

$$I_{ds} = f\left(V_{gs}\right) \tag{21}$$

and

$$I_{ds} = I_{dss}\left(1 - \left(\frac{V_{gs}}{V_{gs-off}}\right)\right)^2, \tag{22}$$

where I_{dss} is equal to the value of I_{ds} when Vgs for the saturation is zero. The I_{dss} and $\mathrm{V_{gs-off}}$ are mostly constant and given for different transistor devices in their technical specifications.

BJTs on the other hand, work as an amplifier in the linear/triode mode and as a switch in the saturation mode [16]. The three modes are shown using the Ids/Vds relationship (output characteristics) at different values of gate voltages

(Vgs) in Figure 28. The slope of the curve gives the reciprocal of the drain-source resistance as a conformation to the basic ohm's law, this resistance value is usually given in technical specifications of semi-conductor switching materials.

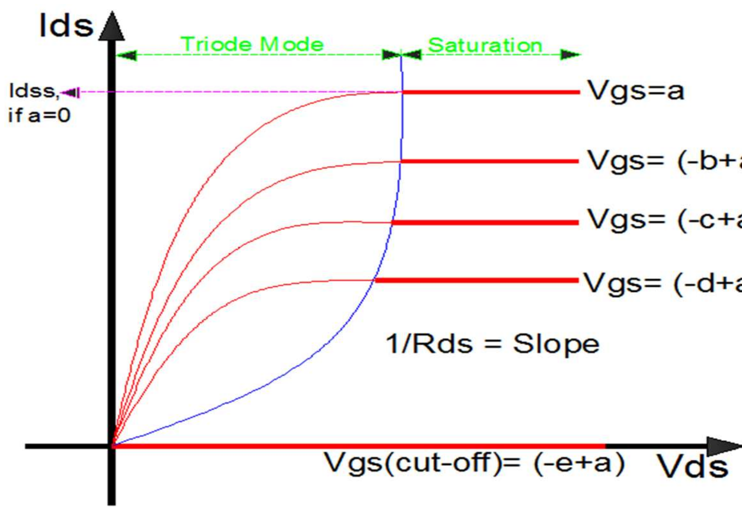


Figure 28 : MOSFET Output Characteristics [17]

The diagram above shows the three modes mentioned, with the blue parabolic line showing the boundary between the triode and saturation mode of a MOSFET. The numbers represented by "-b" and "-e" are in the order of increasing negativity with -e being the most negative number. Having discussed the different modes of MOSFET operation and how they interact, the general symbol and representation in Simscape (Simelectronics) of a n-channel MOSFET is shown below in Figure 29.

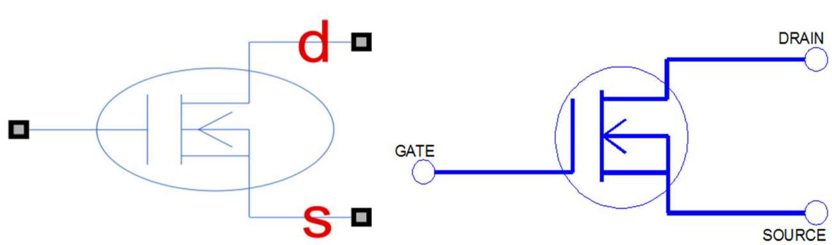


Figure 29 : N-Channel MOSFET Simscape and General Symbol

4.3 Silicon Carbide MOSFET

An important aspect of this research work is the modelling of the power semi-conductor switch to be utilized in the converter. The SiC MOSFET switch is a wide band gap switch of about 2.96eV to 3.3eV suitable for high voltage applications, thereby covering for its present downside, which is the forward voltage drop of about 1 to 1.2V [2,18]. It has a high thermal conductivity of up to 3 times that of normal Silicon devices. It also has a high melting point and can operate well over $400^{o}C$, thereby reducing the cost of cooling (heat sink and external cooling where necessary) [2]. A special feature which made it superior in this application is its ability to work under a high frequency. This feature helps to reduce the size of magnetic components used in filtering (inductors), power transformation and electrical isolation (HF transformer which can be likened to a coupled inductor) [2,18]. The expression for the relationship between reactive impedance and frequency is given as

$$X_L = 2 \cdot \pi \cdot f \cdot L \qquad (23)$$

and

$$f = X_L/(2 \cdot \pi \cdot L). \qquad (24)$$

While,

$$X_C = 1/(2 \cdot \pi \cdot f \cdot C) \qquad (25)$$

and

$$f = 1/(2 \cdot \pi \cdot X\_C \cdot C)\,, \qquad (26)$$

where X_L and X_C are the inductive and capacitive impedances in ohms (Ω),

f, L and C are the frequency (Hertz), inductance (Henry) and capacitance (Farads). The frequencies are inversely proportional to both L and C, thereby, reducing to a large extent, the sizes of these devices. Table 3 below shows the electrical and physical comparison between the conventional Si MOSFET and SiC MOSFET devices. The 4H-SiC and 6H-SiC are the commercially available SiC devices presently.

Table 3 : Si vs SiC MOSFET Comparison [2]

PARAMETER	Si	4H-SiC	6H-SiC	UNIT
Thermal Conductivity	1.5	3.45	3.45	W/cm.K
Band Gap	1.12	3.26	3.03	eV
Critical Electric Field	0.2	2.2	2.4	MV/cm
Dielectric Constant	11.8	9.7	9.7	
Electron Saturated Drift Velocity	10	20	20	Mcm/s

Due to the properties stated above, SiC MOSFETs have properties that make them suitable in different areas of applications. The table below shows different features and their direct benefits as well as their and area of best applications.

Table 4 : SiC MOSFET System Benefits and Applications [19]

FEATURES	SYSTEM BENEFITS	APPLICATIONS
High Frequency	High efficiency operation	Motor Drives
Ultra-Low Loss	Low Thermal Requirements	Induction Heating
Paralleling made easy	Reduced system cost	UPS & SMPS
Zero Turn-Off Tail Current from MOSFET	Reduced need for Over-Voltage Protection	Solar & Wind Inverters (Renewable Energy Harnessing)
Efficient Insulator & Base plate	Enables Miniaturization	Traction

The basic characteristics to be considered in order to confirm that a correct modelling of the SiC MOSFET switch is being carried out are the output and dynamic characteristics. The output characteristics is a plot of the I_{ds} vs V_{ds} at different values of V_{gs}.

Based on the rating of the cascaded converter utilizing the SiC MOSFET, we used an existing SiC MOSFET manufactured by Cree Inc., a trusted semiconductor device company. It is a 1.2KV, 5mohm SiC MOSFET device and the model name is “CAS300M12BM2, 1.2kV, 5.0 mΩ All-Silicon Carbide, Half-Bridge Module, C2M MOSFET and Z-RecTM Diode” [19]. We used the technical parameters for this product to model this device in Simulink (Simscape), which is a library in MATLAB that is flexible enough to allow an in-depth customization of devices in order to achieve simulation results with minimal deviations. The circuit to simulate the output characteristics in Simelectronics is shown below in Figure 30.

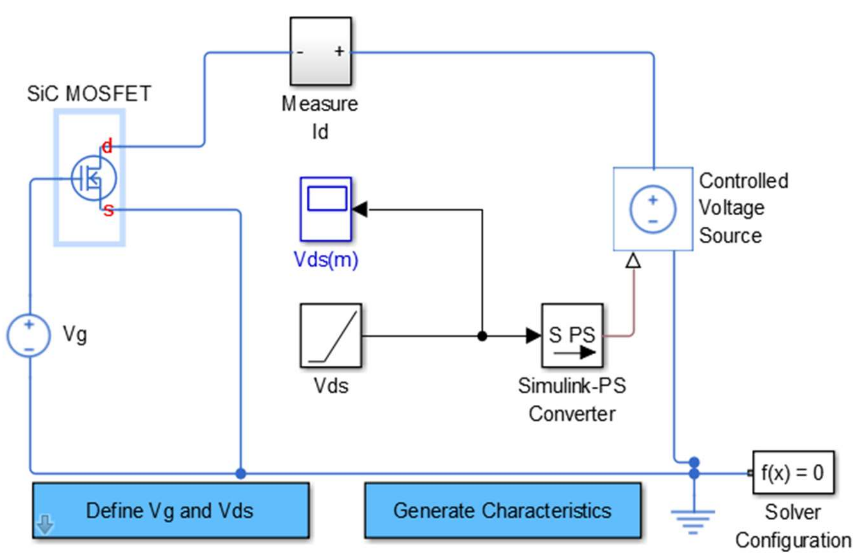


Figure 30 :Output Characteristics Circuit

Different values of V_{gs}, 10V, 12V, 14V, 16V, 18V and 20V were used in this simulation to obtain the different output characteristics [19]. The result obtained from the simulation and the experimental result by Cree Inc. are also given in Figure 31 and Figure 32 respectively.

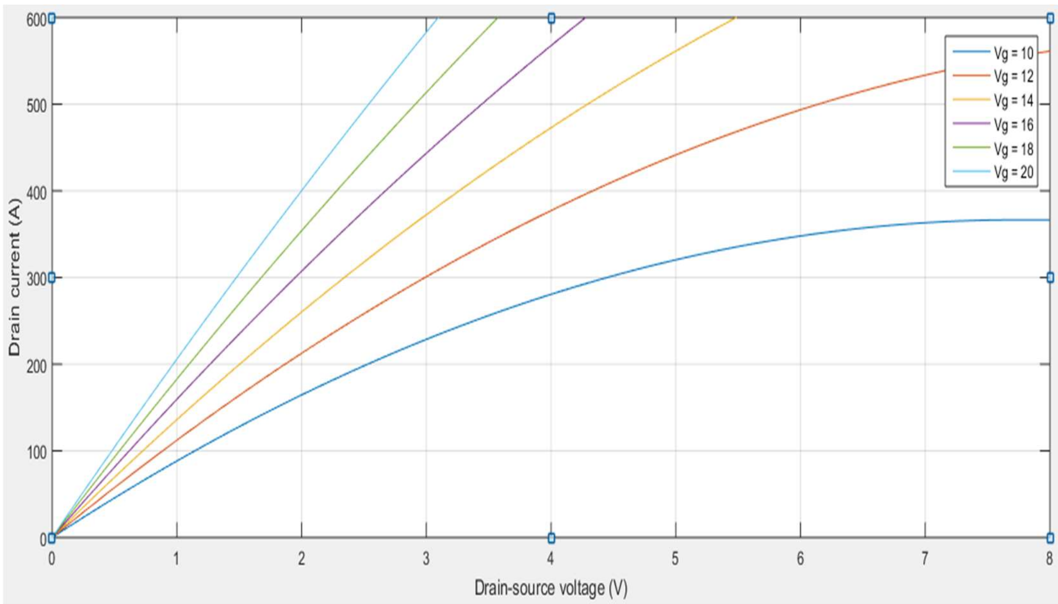


Figure 31 : SiC MOSFET Simulation Output Characteristics at $25^{o}C$

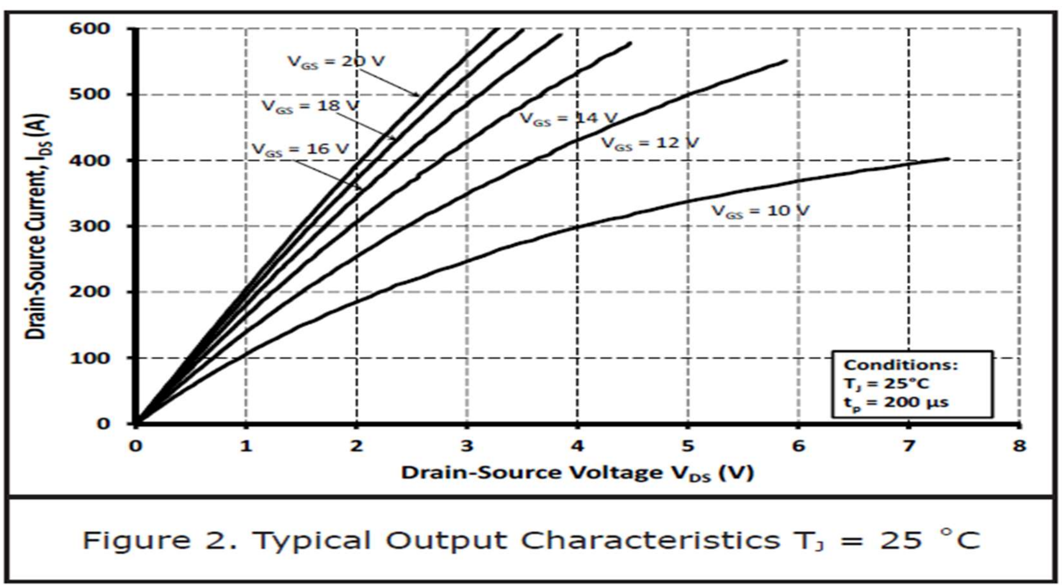


Figure 32 : SiC MOSFET Experimental Output Characteristics at $25^{o}C$

4.3.1 SiC MOSFET Switching Losses

There two kinds of losses involved in MOSFET devices generally are the conduction and switching losses. Conduction loss is a product of the square of the drain-current ($(I_{ds})^2$) when the switch is on, and the on-state resistance (R_{ds}). In a period, the average conduction loss is obtained by multiplying the product by the duty ratio (0.5 in this case) of the switch. This is the on-state power loss, the off-state can be calculated by using the leakage current and it is usually negligible. The conduction power loss is given as

$$\mathrm{P_{cond}} = (\mathrm{Ids_{on}})^2 \cdot \mathrm{D} \cdot \mathrm{Rds_{on}}. \tag{27}$$

Switching losses on the other hand are products of non-zero drain current and drain to source voltage. Ideal switches have zero rise times, fall times, turn-off times and turn-off times, therefore, have zero switching losses. However, ideal switches are impractical and for real switches, the values are non-zeros and can be obtained using the equation given as

$$P_{sw} = \left(V_{off} \cdot I_{on} \cdot f_s\right)\left(t_{\frac{on}{2}} + t_{\frac{off}{2}}\right), \tag{28}$$

where t_{on} and t_{off} are turn-on and turn-off times respectively [20,21].

The turn-on losses are most times different from the turn-off losses, depending on the switch adopted and the switching frequency. The lower the switching frequency, the lower the switching loss and vice versa. This is the reason for the continuous need for a trade-off between efficiency and power density (size). The rise-time and fall time are very important in determining the switching loss as they directly interfere with the time in which both current and voltage are simultaneously non-zero values. The rise-time, fall-time, turn-on energy and turn-off energy of the SiC MOSFET was obtained by carrying out the simulation as shown in Figure 33.

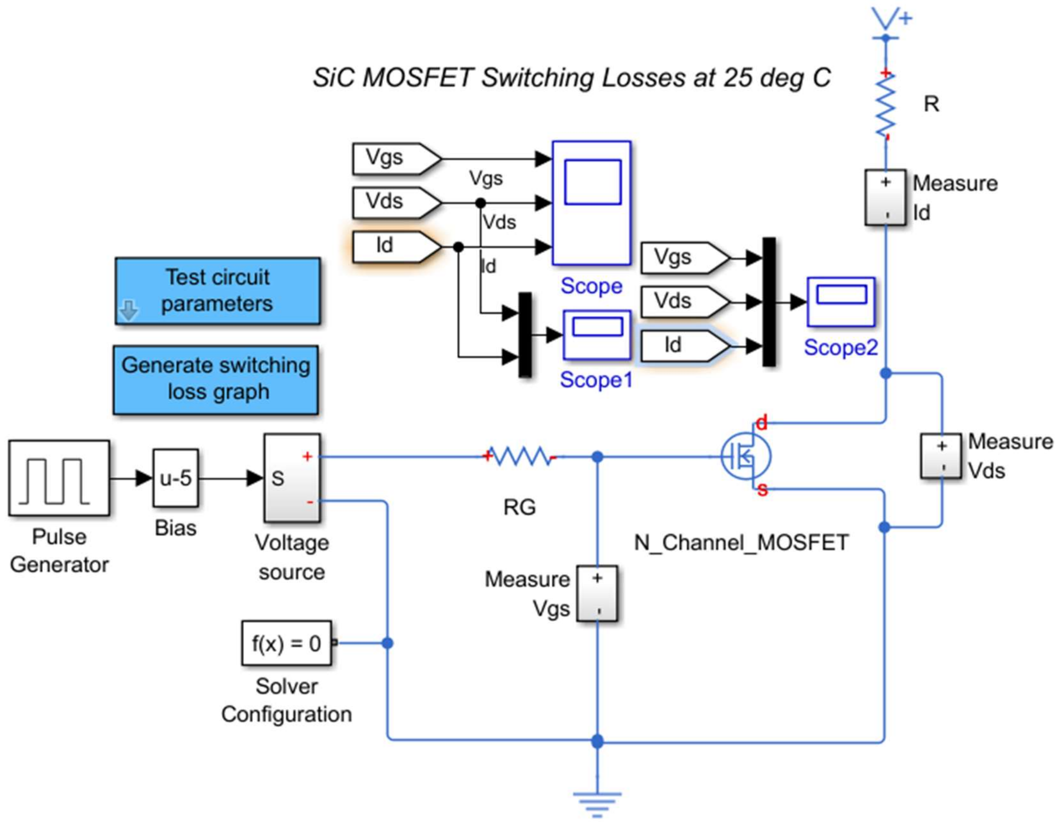


Figure 33 : SiC MOSFET Switching Loss Circuit

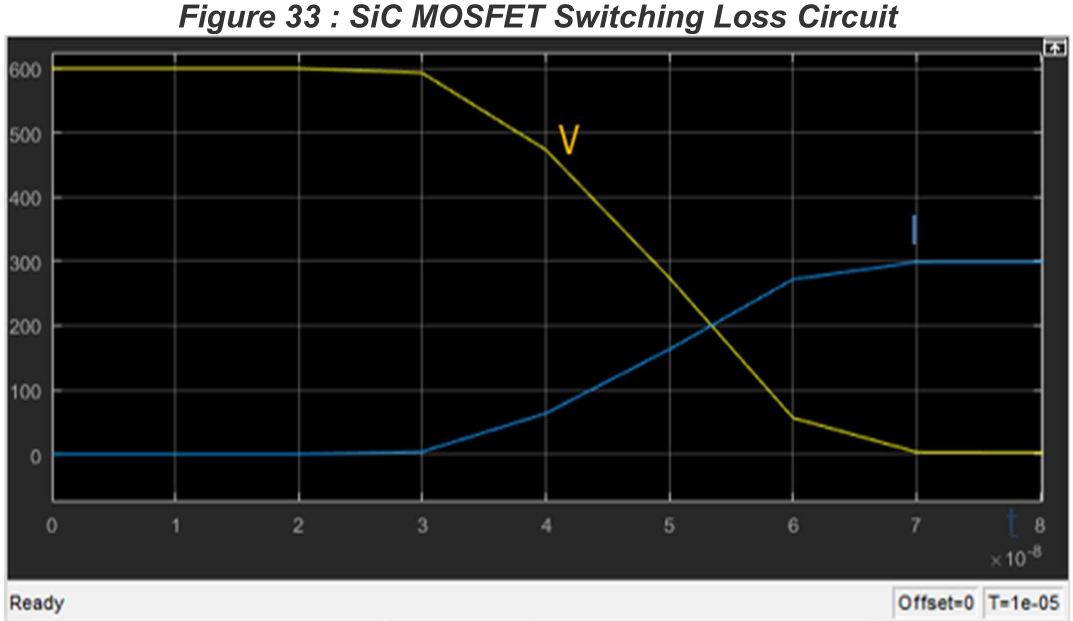


Figure 34 : SiC MOSFET Turn-on

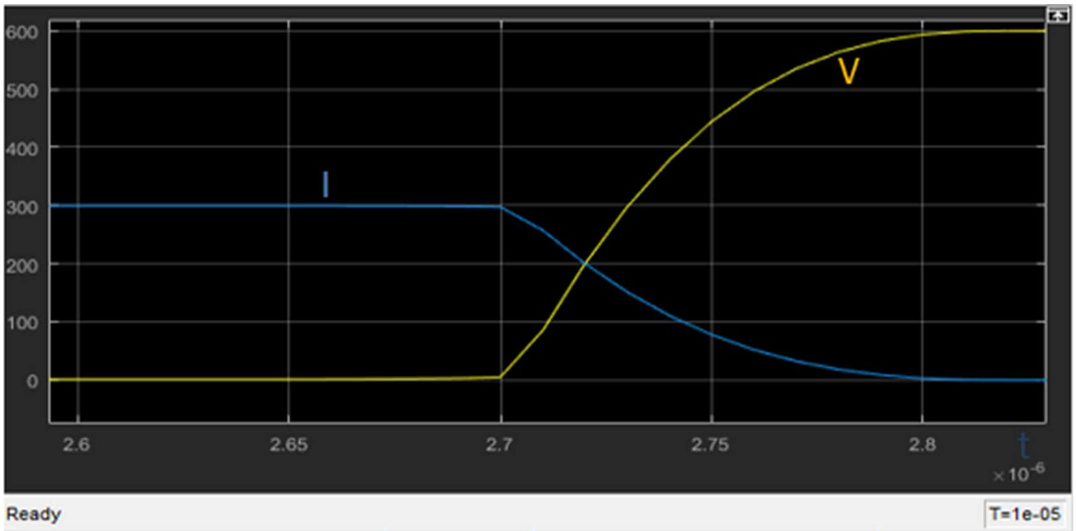


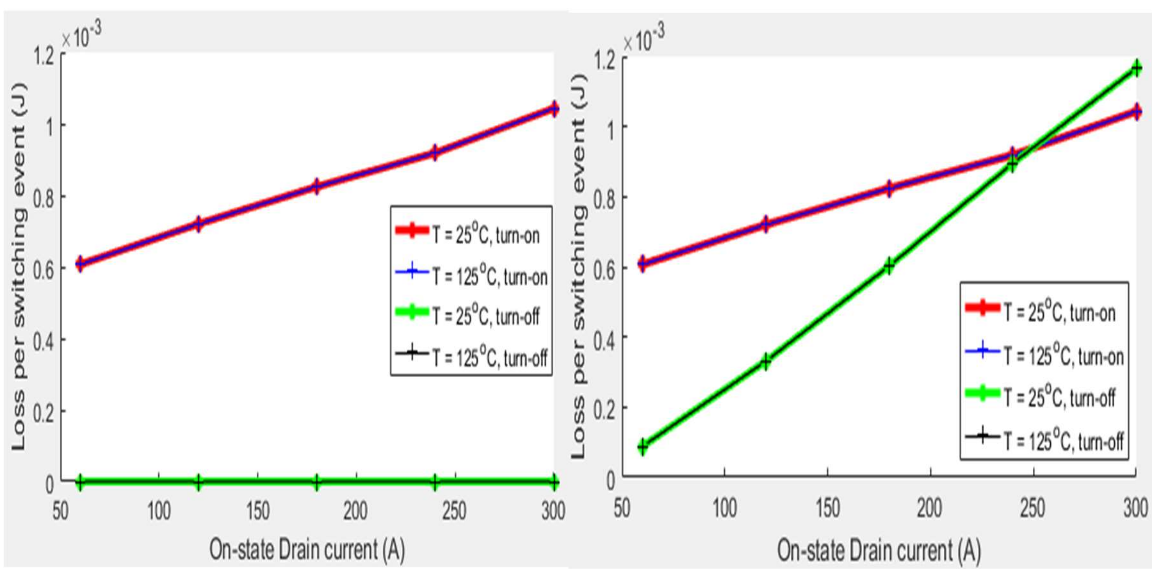
Figure 35 : SiC MOSFET Turn-off

The rise time from Figure 34 can be estimated as

$$(7-3)e^{-8}=(4)e^{-8}\ s, \qquad (29)$$

while the fall-time from Figure 35 can be estimated as

$$(2.8-2.7)e^{-6}=(1)e^{-5}s. \qquad (30)$$



(a) (b)

Figure 36 : SiC Switching Energy at (a) 20KHz and (b) 200KHz

From Figure 36(a) and (b), the switching energy can be traced and this is estimated as $(0.7)e^{-3}$ J at 20KHz and $(1.1)e^{-3}$J at 200KHz.

Another form of loss that has to do with charging and discharging of the parasitic capacitor is sometimes taken into consideration by [20] [21], this is given by

$$P_{sw}C_{oss} = C_{oss} \cdot \left(V_{off}\right)^2 \cdot f_s. \tag{31}$$

Having stated the above relationships, the total loss in the system is given as

$$P_T = P_{condT} + P_{swT} \,, \tag{32}$$

where P_T is total converter loss, P_{condT} is total conduction loss and P_{swT} is total switching loss.

Considering the Dual-Active Bridge, which is where the control is being carried out as well utilization of the SiC MOSFET devices, the input and output switches make a total of 8 MOSFET devices in the DC-DC converter. With a 1:1 turns-ratio of the HF transformer, we can assume the same voltage for both sides, therefore, the overall conduction loss is given as

$$P_{condT} = 8 \cdot P_{cond,} \tag{33}$$

while the overall switching loss can also be given as

$$P_{swT} = 8 \cdot P_{sw}. \tag{34}$$

From *Eq. 27* Conduction loss can be calculated as

$$P_{cond} = (Ids_{on})^2 \cdot 0.5 \cdot 0.005 = (100)^2 \cdot 0.5 \cdot 0.005 = 25W. \tag{35}$$

Having obtained the Switching energy of the Converter in *Figure 40* , the switching Loss can be expressed as

$$P_{sw} = (P_{sw}\ at\ turn-on) + (P_{sw}\ at\ turn-off). \tag{36}$$

At 20KHz, the switching loss at turn-off can be assumed to be zero unlike 200KHz operation, therefore,

$$P_{sw} = (P_{sw}\ at\ turn - on) = E_{on} \cdot \left(\frac{V \cdot I}{V_{ref} \cdot I_{ref}}\right) \cdot f_s \,, \tag{37}$$

where E_{on} is the switching energy at turn-on, V_{ref} and I_{ref} are the reference voltage and current of the SiC switching device, symbol, f_s is switching frequency, while V and I are the operating voltage and current. The switching power loss is given as

$$P_{sw} = (0.7)e^{-3} \cdot \left(\frac{600 \cdot 100}{1200 \cdot 300}\right) \cdot 20000 = 2.33\ W. \tag{38}$$

Making use of the values obtained and the overall formula, we have the total loss given as

$$P_T = P_{condT} + P_{swT} = P_T = 8 \cdot (P_{cond} + P_{sw}) \tag{39}$$

and

$$P_T = 8 \cdot (25 + 2.33)W = 218.64W. \tag{40}$$

CHAPTER 5 SIMULATION AND RESULT

In this section, the simulation of the different converters that make up each module and the whole cascaded system described in chapter 3 will be shown along with the results.

5.1 Full-Bridge Active Rectifier

As stated in the abstract, the Simulations were carried out using Simscape library in MATLAB (Simelectronics). Simulations were done in Simpower (literature review) and Simscape (Simelectronics) but the later will be shown for subsequent simulations as it gives a more accurate result despite being a bit more complex to implement when simulating complex (cascaded) systems. The full bridge Active Rectifier simulation in Simscape/Simelectronics is shown below in Figure 37 .

A very important portion of this converter is the filtering circuit- an output capacitor filter, this helps to reduce the output voltage ripple in order to avoid excessive pulses in the output DC as some loads are very sensitive and require the cleanest form of DC possible. Another way to view this is that the period of the pulsating DC in a half bridge rectifier is 2 times the period in a full-wave rectifier which makes the filtering easier, although, the peak voltage in the full-wave is a bit lower than that of the half-wave because there are four voltage drops (four switches) in the full-wave rectification. As opposed to a half wave rectifier, due to the rectified sine wave in the second half of each period in a full-wave rectifier, the output filter discharges in a shorter time.

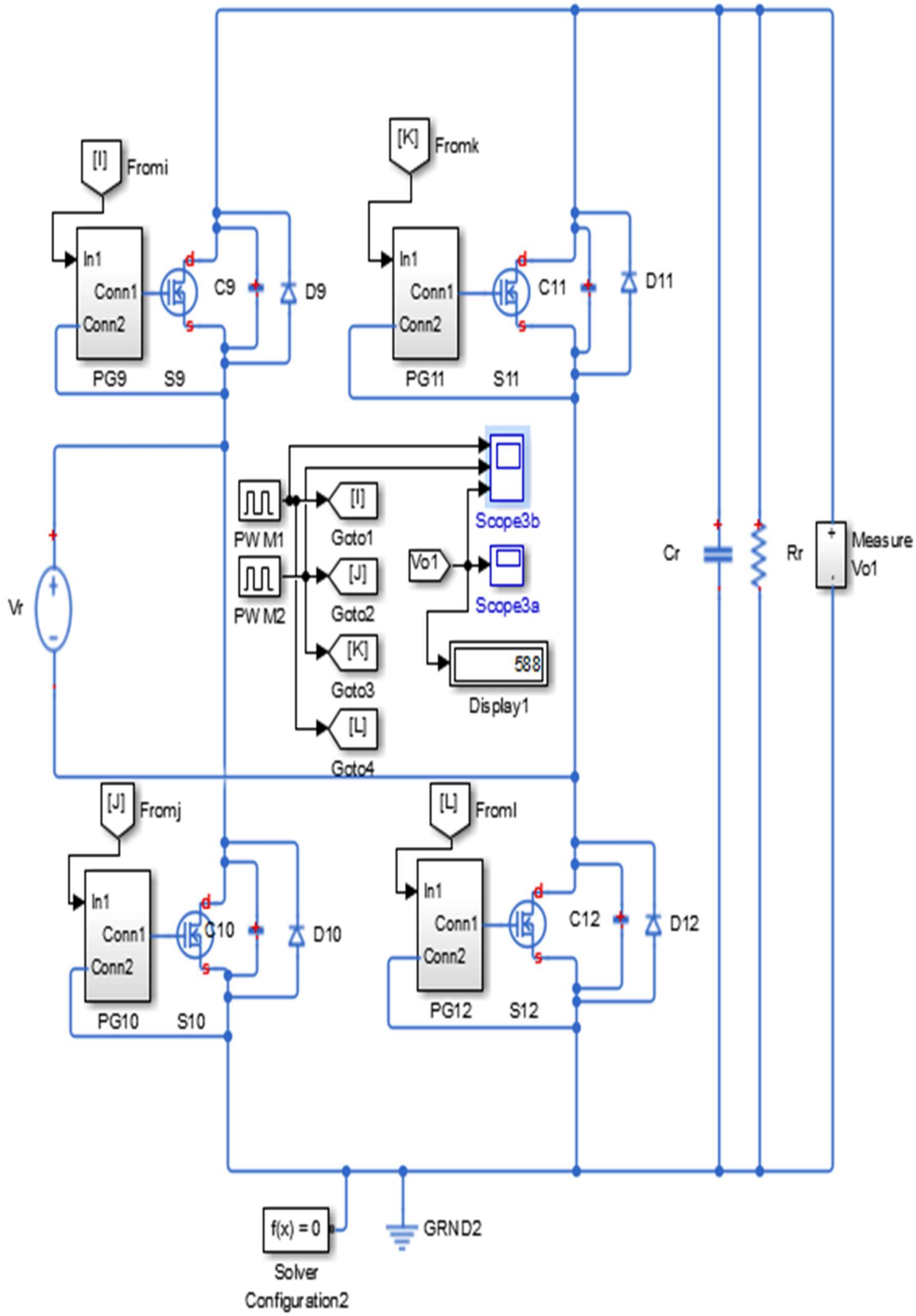


Figure 37 : Full Bridge Bi-directional Active Rectifier

A maximum ripple of 0.1% was adopted all through the simulations when necessary for the purpose of uniformity. The voltage ripple is given by

$$\Delta V_o = V_m \pi / \omega RC, \tag{41}$$

where V_m is the maximum voltage which is equal to $Vin * \sqrt{2}$, and ω is the angular frequency, which is equal to $2\pi f$ [1]. Therefore, the voltage ripple can be re-written as

$$\Delta V_o = V_m / 2fRC. \tag{42}$$

By making use of the relationship between the maximum voltage and the root mean square voltage, we have the maximum voltage given as

$$V_m = 600 \cdot \sqrt{2} = 848.5. \tag{43}$$

Introducing the filtering capacitor of 100mH and resistance of 100ohms, we have the voltage ripple given as

$$\Delta V_o = \frac{848.5}{2 \cdot 60 \cdot 10 \quad \cdot 0.1} = 0.707V. \tag{44}$$

The percentage ripple is therefore given as

$$\Delta V_o = \frac{0.707}{848.5} \cdot 100 = 0.083\%. \tag{45}$$

The output is shown through the Simscape scope in Figure 38.

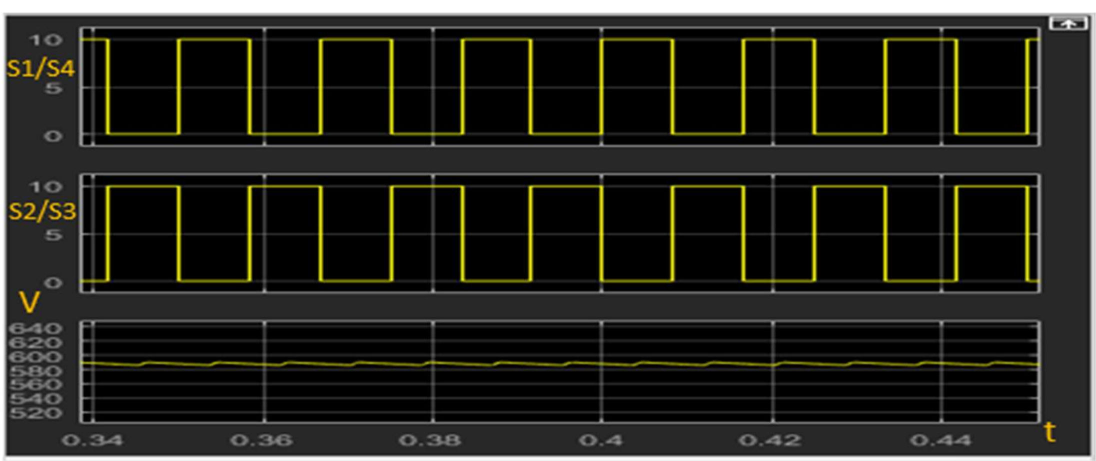


Figure 38 : Full Bridge Active Rectifier Switching Signal and Output Voltage

The first 2 rows in Figure 38 indicate the alternate switching of the diagonally paired switches and the last row shows the filtered output DC voltage. The output can be varied by varying the filtering parameters depending on the sensitivity and nature of the load.

5.2 Full-Bridge Active Inverter

This is the output section where the output of the DC-DC converter is inverted (converted to AC) whose frequency is a function of the selected frequency. As shown in Figure 17 and Figure 18, this can be achieved by reversing the input and output of the described full-bridge active rectifier. The simulation in Simscape (Simelectronics) are shown in Figure 39 and Figure 40 .

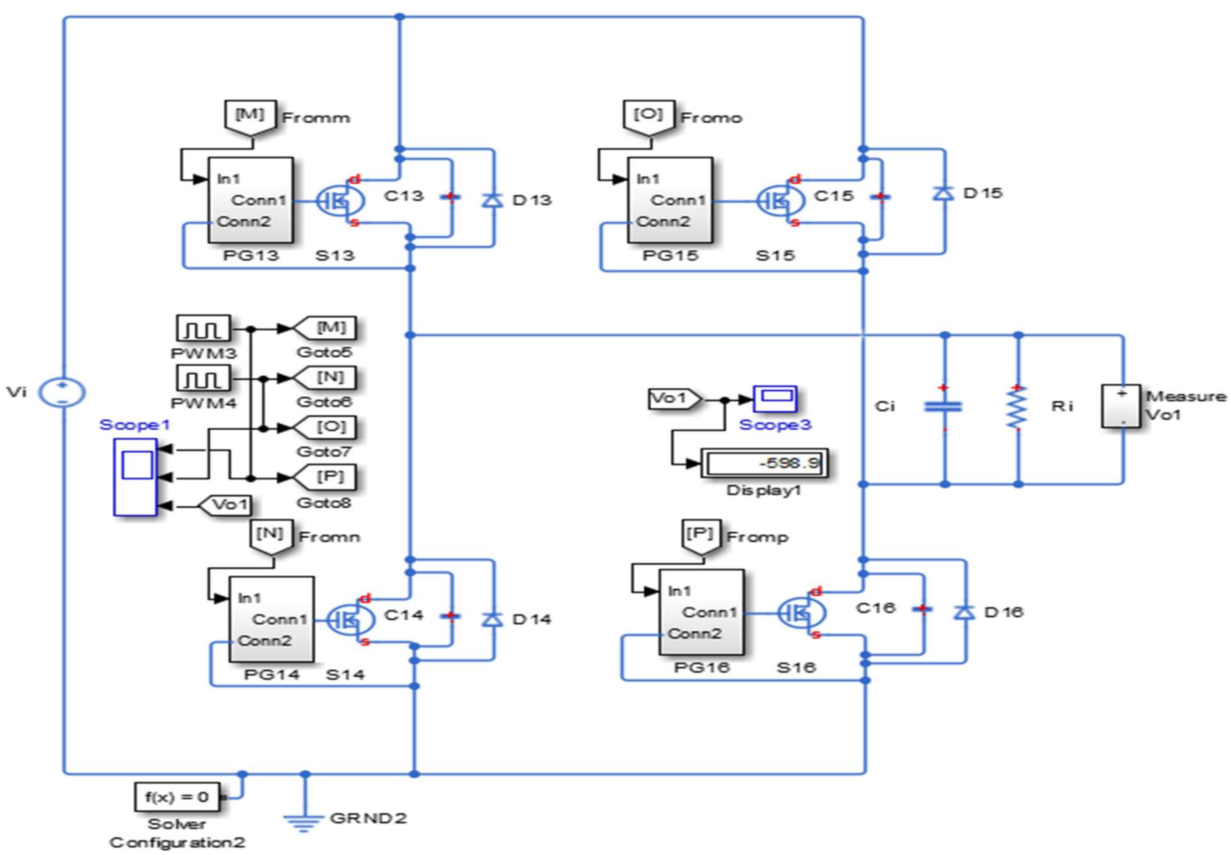


Figure 39 : Full-Bridge Active Inverter

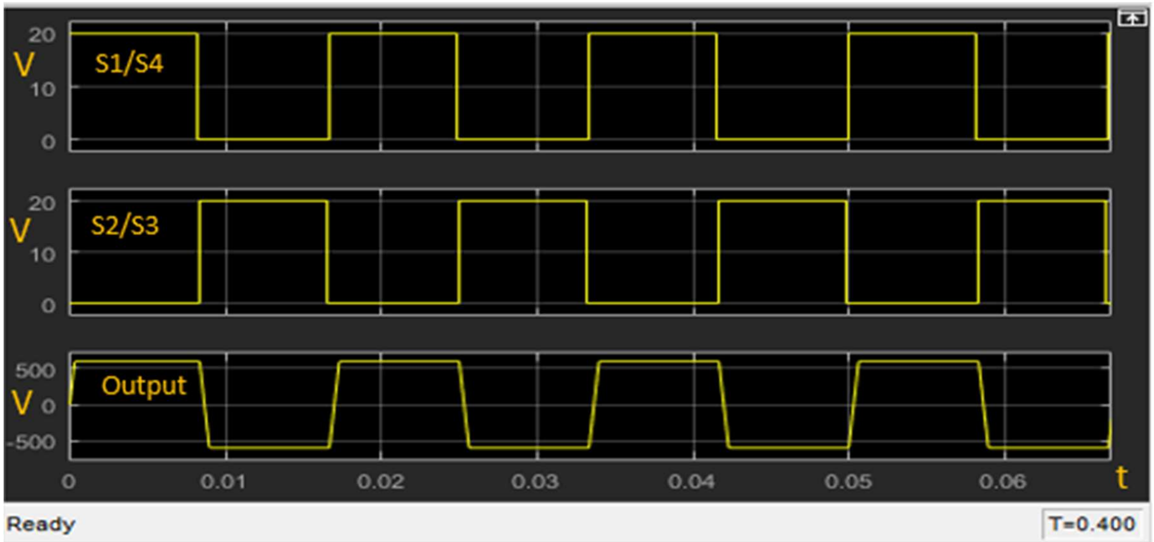


Figure 40 : Switching Signals & Output V for Full-Bridge Active Inverter

With an input of 600VDC, the first two rows are the paired alternating switching signals ($V_{gs} = 20V$) and the last row is the square-wave AC output voltage at 60Hz.

5.3 Bi-directional Dual Active Bridge (BDAB)

The simulation schematic for the BDAB is shown in Figure 41, switch coordination in Figure 42, and the outputs for different conditions are shown in, Figure 43 and Figure 44. Note that the switches in Figure 41 were made as subsystem in order to allow for a clean and flexible simulation. PGAD is the gate signal for switch 1 (S1) and switch 2 (S4), PGBC is for switch 2 (S2) and switch 3 (S3), PGEH is for switch 5 (S5) and switch 8 (S8) while PGFG is for switch 6 (S6) and switch 7 (S7). The phase shift shown in Figure 42 is used to control the power flow direction as explained earlier, when the phase shift is swapped between the input and the output bridge the direction is reversed (analogous to the conventional power flow equation) [9,10,11].

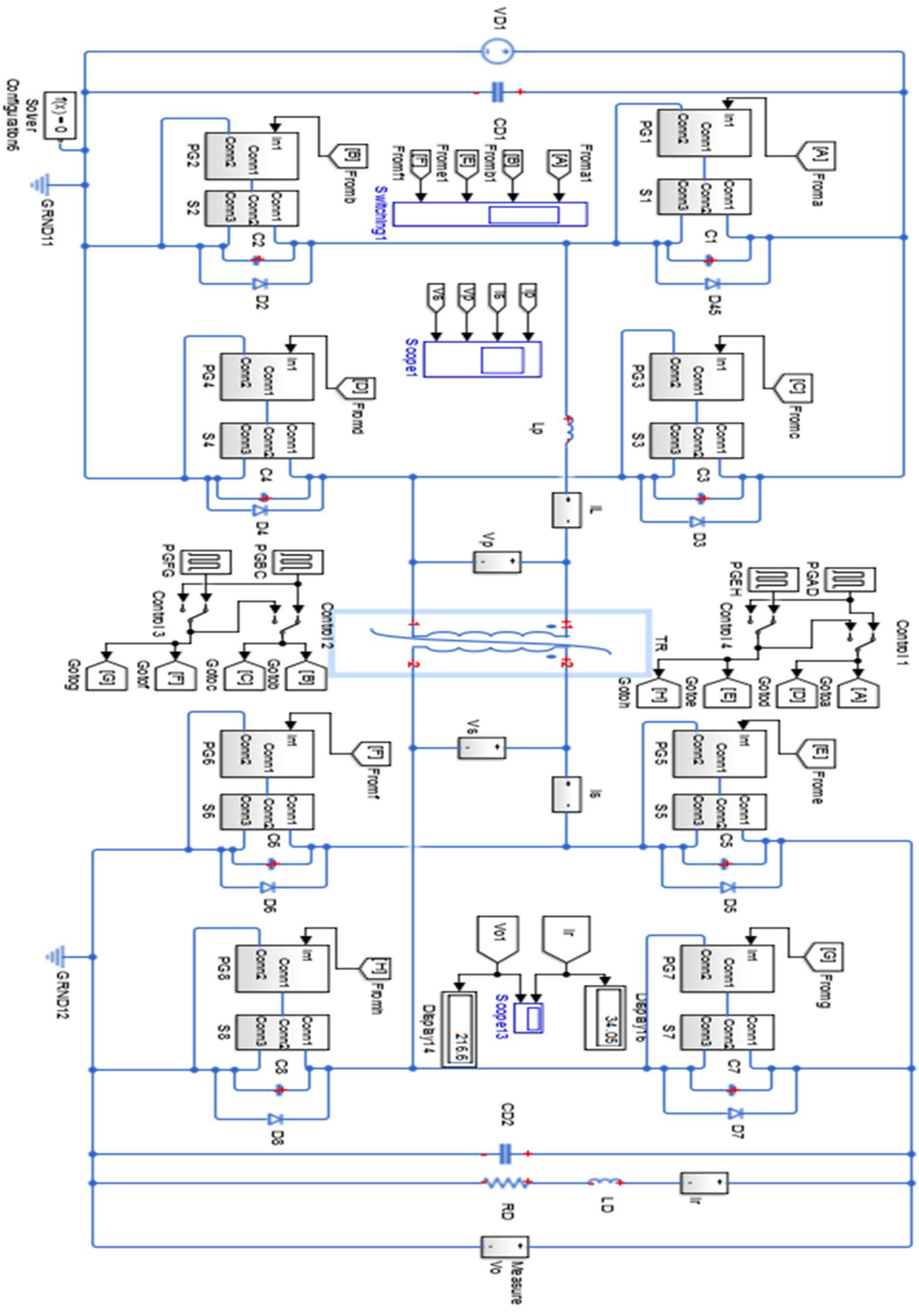


Figure 41 :Bi-directional Dual Active Bridge

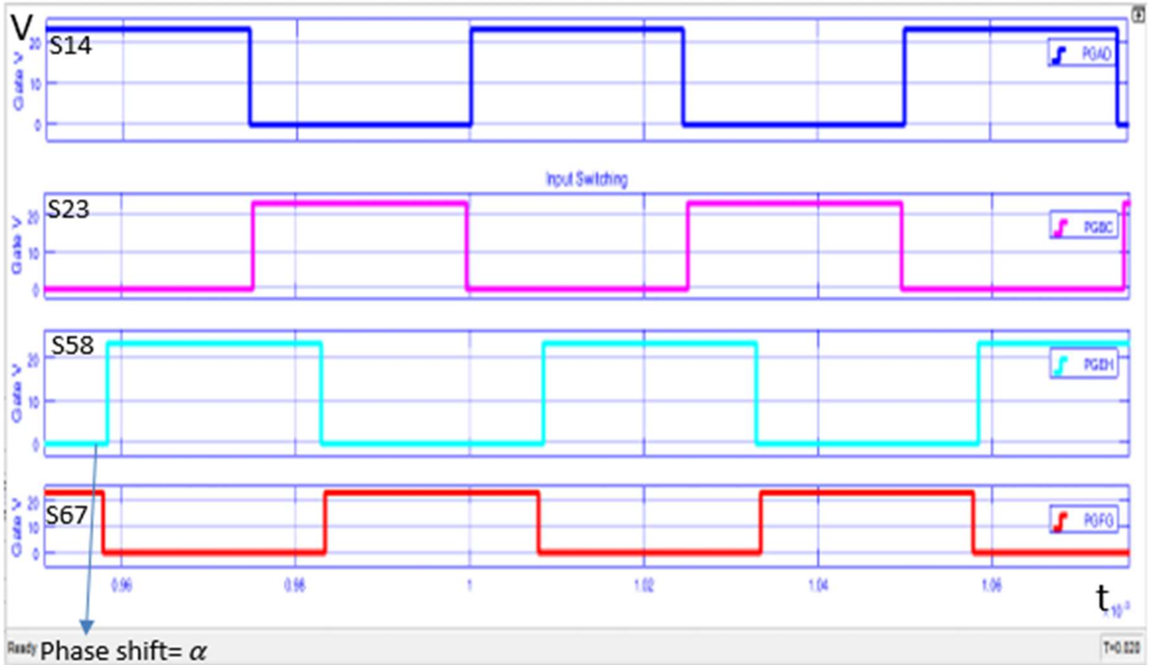


Figure 42 : BDAB Gate Voltage Switching Topology

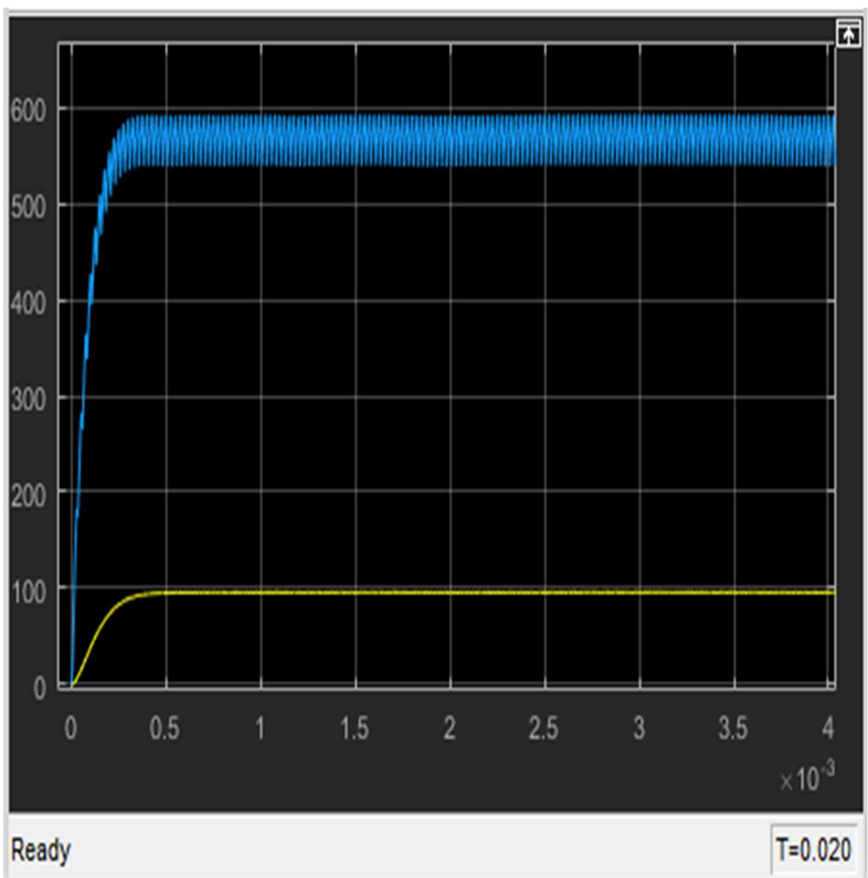


Figure 43 : BDAB Output Voltage and Current at 50% Duty Ratio

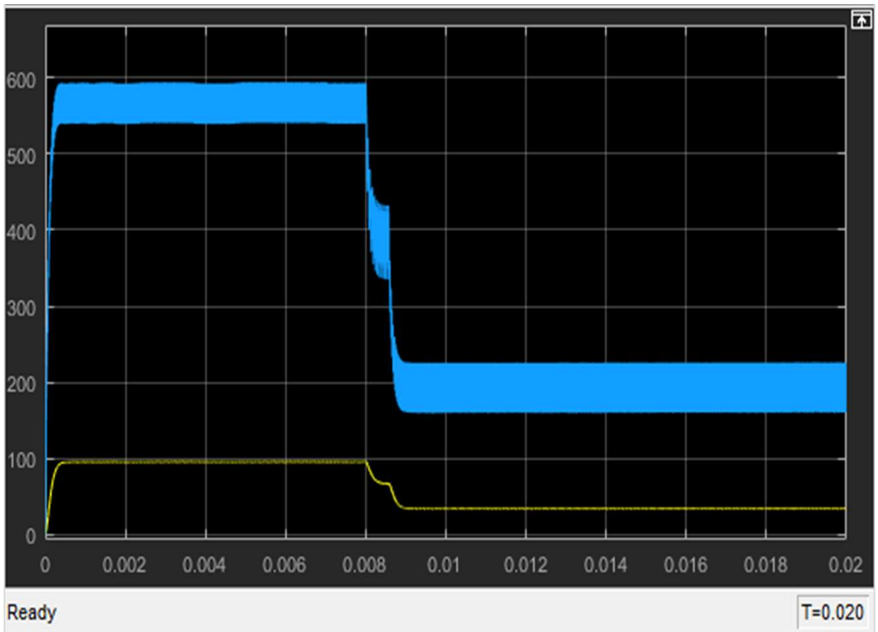


Figure 44 : BDAB Output Voltage and Current from 50% to 30% Duty Ratio

The circuit was tested for both resistive and inductive load conditions in order to check for the effect on the circuit. The output scope in Figure 44 shows the output voltage (blue signal) and current (yellow) for a complete 50% duty ratio of the input switches and the output scope in Figure 44 shows the output voltage (blue signal) and current (yellow), starting from 50% and changed to 30% duty ratio of the input switches in order to show the flexibility. The ripple can as usual be manipulated by varying the value of the filtering capacitor.

5.4 Power Converter Module

This power module as described in chapter three is a combination of the rectifier, BDAB, and the Inverter. We made each converter bi-directional in order to avoid defeating the purpose and flexibility of the topology. The arrangement and output are shown in Figure 45 and Figure 46 .

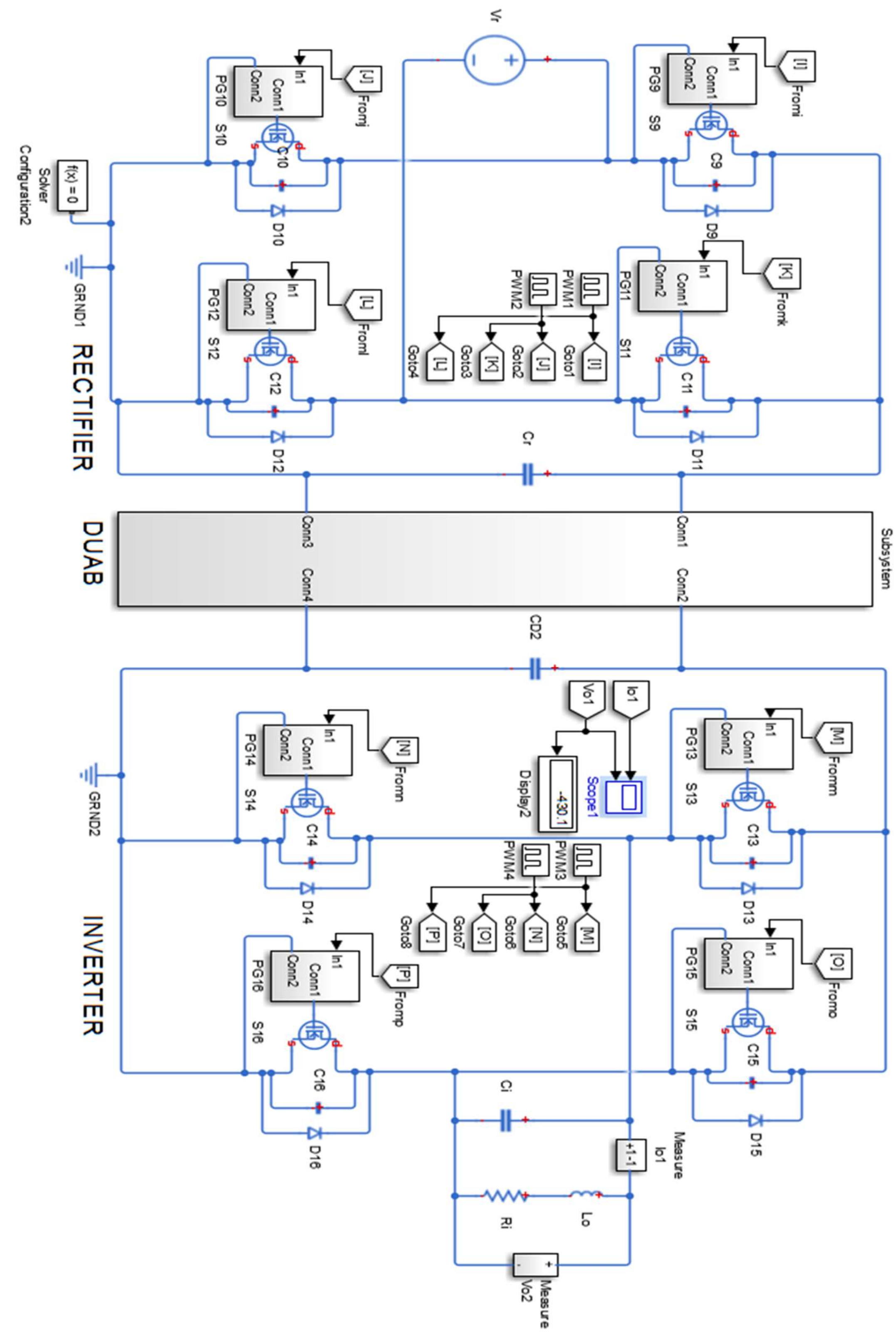


Figure 45 : Converter Module in SimElectronics

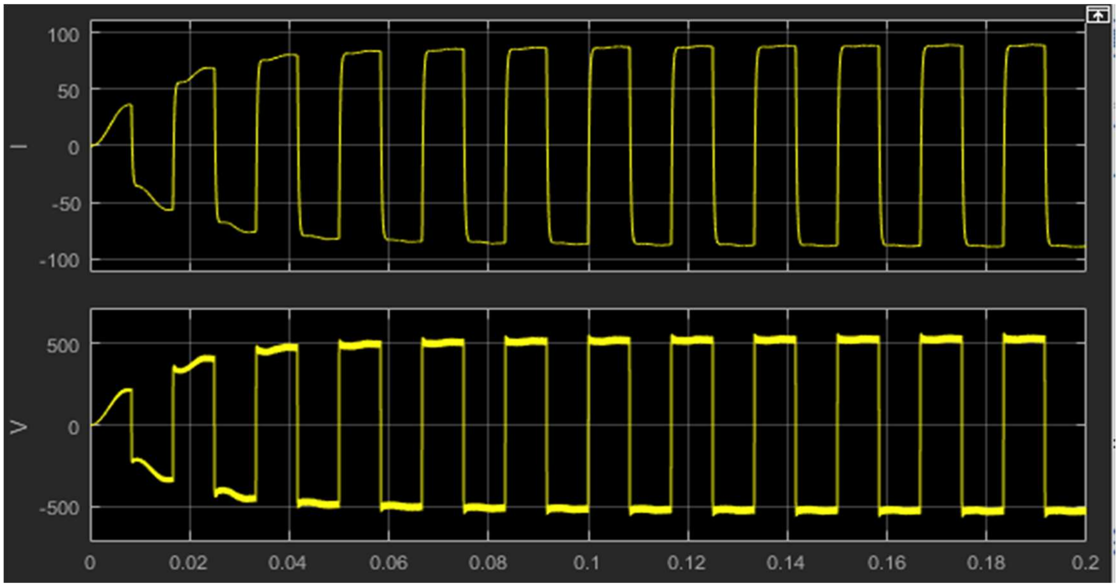


Figure 46 : Converter Module Output Current & Voltage

The output above is the overall output voltage of the Module (rectifier + BDUAB + inverter) which increases steadily due to the varying operating frequency of the individual converters. The rectifier works at a frequency of 60Hz, the BDUAB works at 20KHz and can go higher based on the design (the SiC MOSFET advantage) and the inverter which works at a frequency of 60Hz in this simulation but can also go as high as 6KHz based on load requirement. The period of the module is the period of operation of the converter at the output stage (inverter). If there is a converter whose switches turn on and off at a higher frequency before the output converter, the oscillating effect will be seen in the final output at almost every supposedly steady time range. This is simply because of the reciprocal relationship between the frequency and the period which is mathematically given as

$$T = \left(\frac{1}{60Hz} > \frac{1}{1000Hz} > \frac{1}{6000Hz} > \frac{1}{200000Hz}\right). \qquad (46)$$

5.5 Cascaded Module

As discussed earlier in chapter 3, this is the converter obtained when the individual modules are connected in series making a sting, and then three strings are Y-connected to obtain the three phase cascaded topology. In this case, 4 modules are connected in series before connecting three strings to achieve a three phase system. A phase shift of +120 degrees and -120 degrees are introduced to two of the phases to obtain a non-overlapping accurate three phase system. The simulation, as indicated above was done in both Simpower and SimElectronics, tapping into the benefits of both libraries in MATLAB/Simulink. Each module is put in a subsystem to allow for a clean and flexible simulation as shown in Figure 47

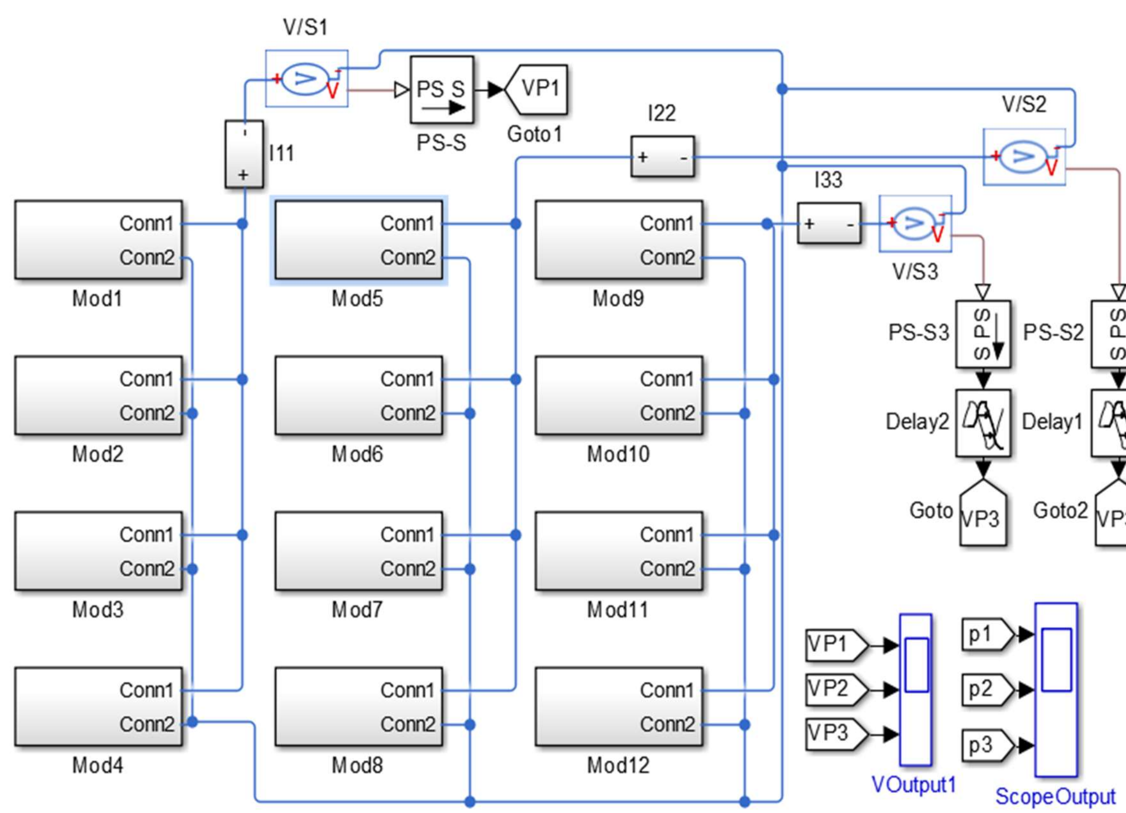


Figure 47 : Overall Multi-level Converter Simulation Layout.

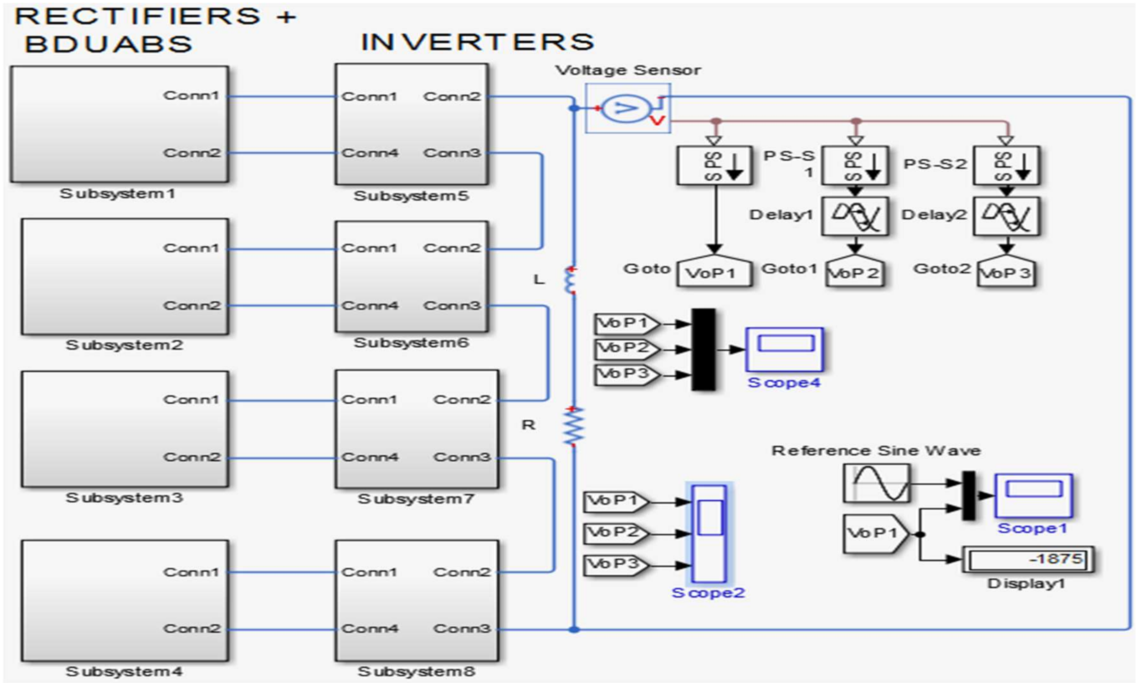


Figure 48 : Series Connected Converter Simulation Layout.

The simulation was carried out considering different scenarios in order to evaluate how the converter respond to changes in load, duty ratio and frequency of operation. At each frequency, the simulation is also carried out for 50% and 100% voltage levels to ensure the control compatibility of the design.

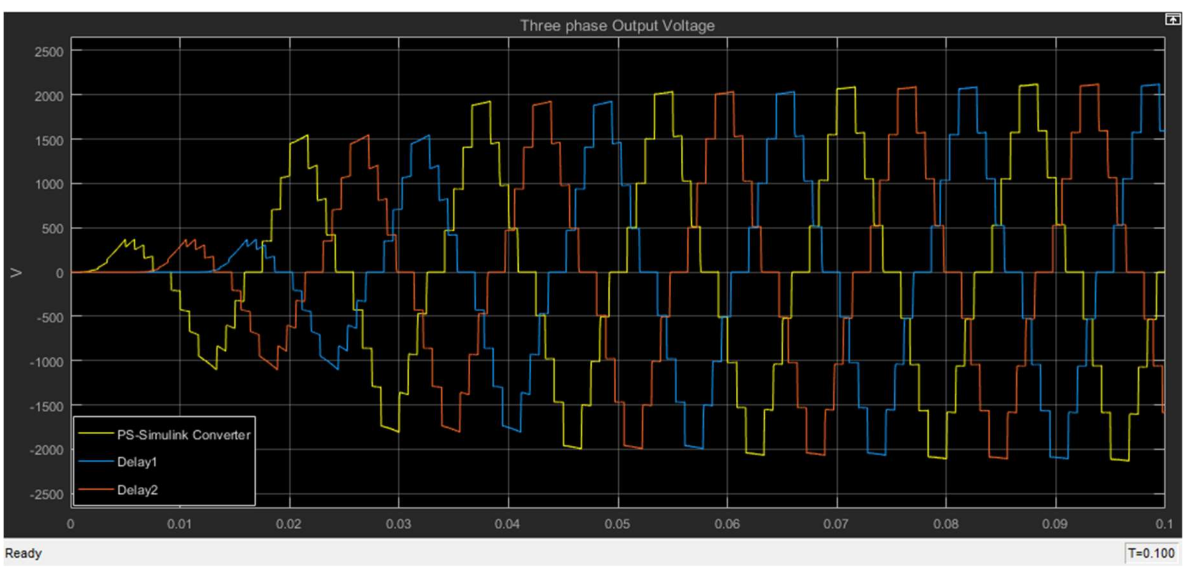


Figure 49 : Multi-level Three Phase Output Voltage at 60Hz

In order to obtain the other two phases, a phase shifter was used- a positive 120 degrees and a positive 240 degrees (-120 degree) delays were introduced, the three phases are shown in Figure 49 with a period of 0.016s (1/60Hz).

Case 1: at a frequency of 60Hz, the single phase 100% and 50% (with 100% reference sine wave) output voltage are shown in Figure 50 and Figure 51 respectively.

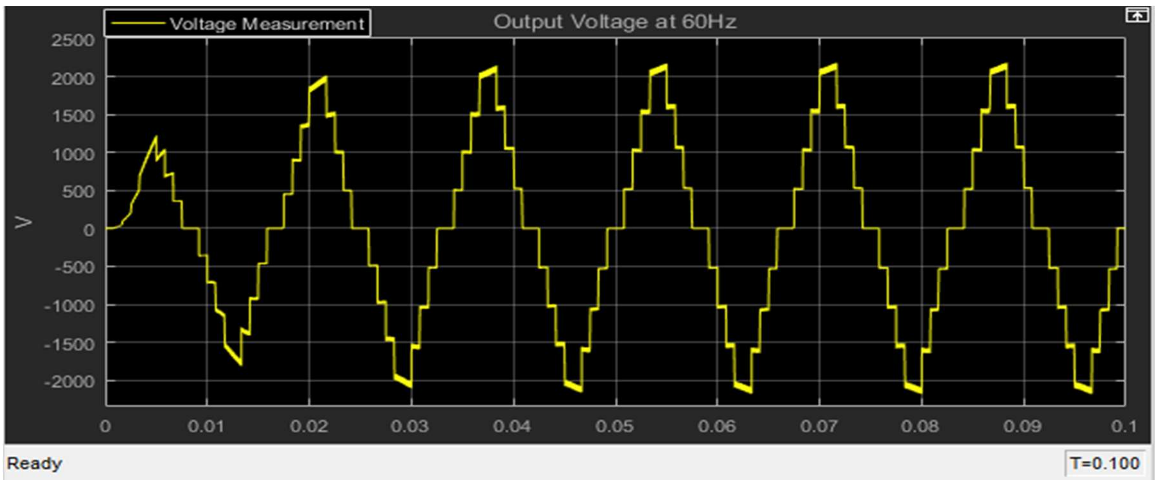


Figure 50 : Multi-level 100% Output Voltage at 60Hz.

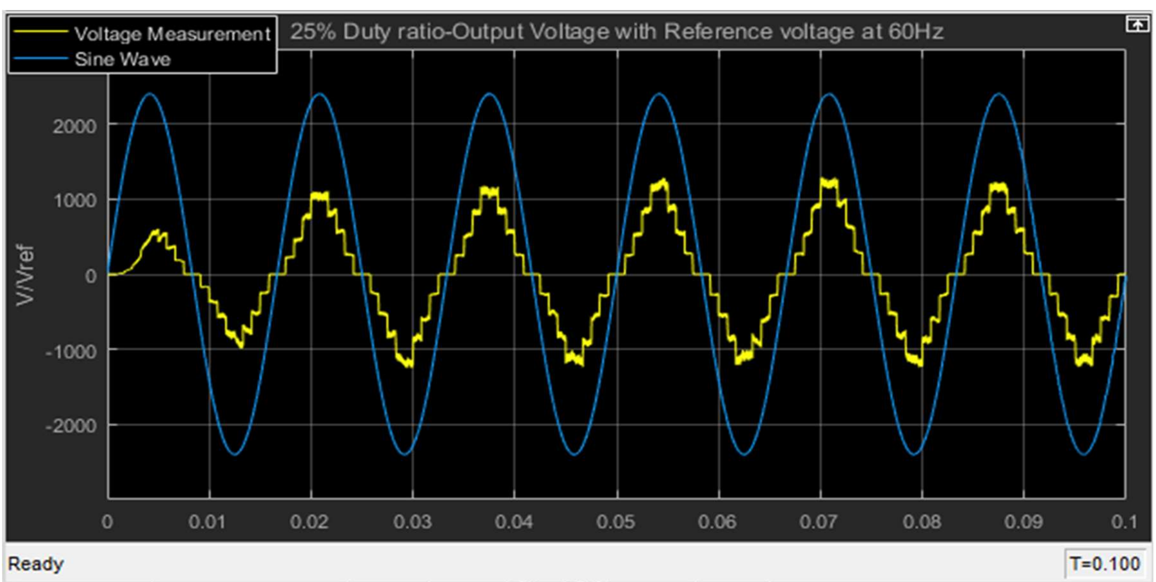


Figure 51 : Multi-level 50% Output Voltage at 60Hz.

The output was controlled by varying the duty ratio of the input full Bridge of the Bi-directional Dual Active Bridge in the module. Figure 51 shows a reference sine wave along with the output voltage at 25% duty ratio. A 50% duty-ratio, as explained will give a 100% output, while a 25% duty-ratio will give a 50% output.

Case 2: at a frequency of 30Hz, the single phase 100% and 50% (with 100% reference sine wave) output voltage are shown in Figure 52 and Figure 53 respectively.

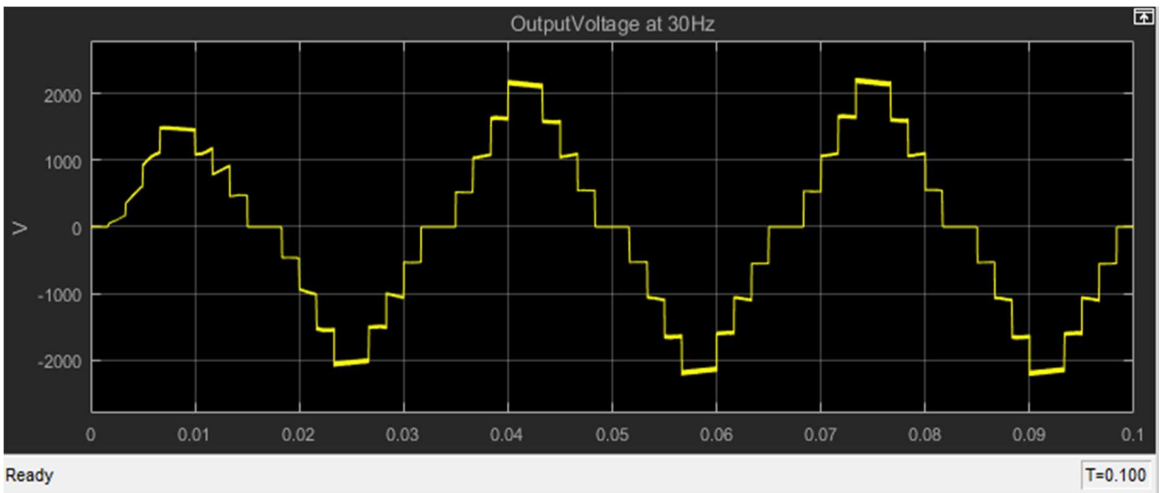


Figure 52 : Multi-level 100% Output Voltage at 30Hz.

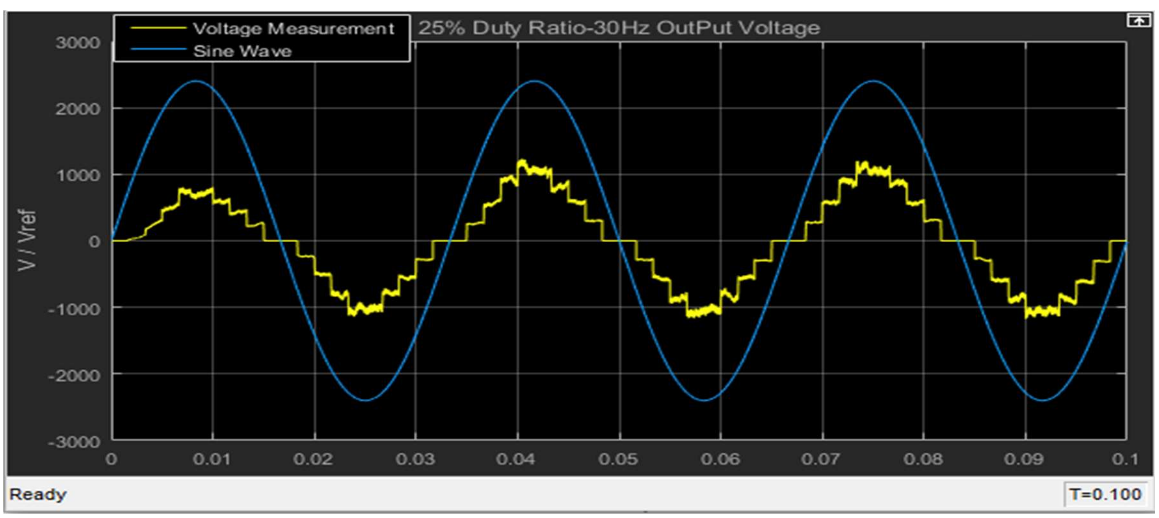


Figure 53 : Multi-level 50% Output Voltage at 30Hz.

Case 3: at a frequency of 120Hz, the single phase 100% and 50% (with 100% reference sine wave) output voltage are shown in Figure 54 and Figure 55 respectively.

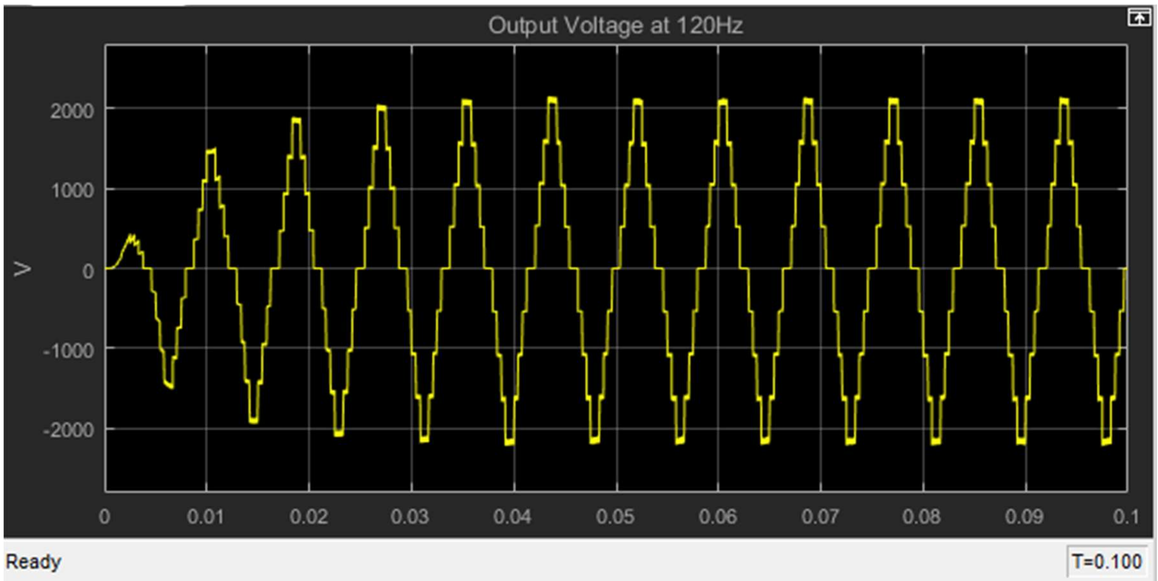


Figure 54 : Multi-level 100% Output Voltage at 120Hz and.

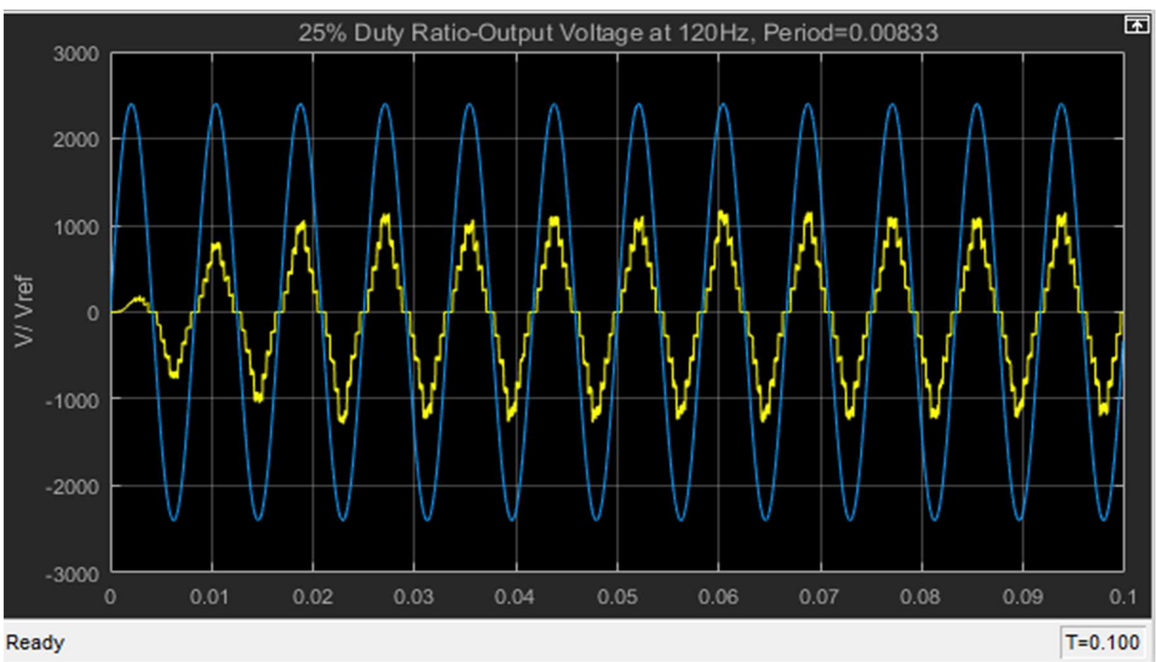


Figure 55 : Multi-level 50% Output Voltage at 120Hz.

CHAPTER 6 CONCLUSION

The purpose of this thesis is basically to analyze the build-up of a converter topology, starting from individual converters that make up each module to the cascaded module as a whole. An important aspect of this cascade is the DC-DC conversion stage as this is the portion where we carry out the magnitude and direction control of the module. We started from the most basic form of DC conversion (literature review), through the non-complex switching converter to the complex ones with the aim of showing the growth in the field of power electronics through various researchers.

The semi-conductor device will enhance to a great extent, the performance of converters, increasing the efficiency, reducing the overall size due to the improved ability of the switches to work at a very high frequency, thereby reducing the magnetic components and these in turn will lead to a more efficient and effective way of energy conversion and transfer. The topology will not only contribute to the efficiency increase at the load side (industrial machines- motor) but also an improvement in harnessing the ever abundant renewable sources of energy, its applicability and compatibility with HVDC transmission.

Lastly, the simulations in this research will serve as an eye-opener in using Simscape (Simelectronics) library in MATLAB as it offers a high level of flexibility and accuracy in modelling electrical and electronic devices and simulation of different electrical systems.

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APPENDIX A

Datasheet: CAS300M12BM2, Rev. -

CAS300M12BM2

1.2kV, 5.0 mΩ All-Silicon Carbide Half-Bridge Module

C2M MOSFET and Z-Rec™ Diode

V_{DS}	1.2 kV
$E_{sw, Total\ @\ 300A}$	12.0 mJ
$R_{DS(on)}$	5.0 mΩ

Features

- Ultra Low Loss
- High-Frequency Operation
- Zero Reverse Recovery Current from Diode
- Zero Turn-off Tail Current from MOSFET
- Normally-off, Fail-safe Device Operation
- Ease of Paralleling
- Copper Baseplate and Aluminum Nitride Insulator

Package 62mm x 106mm x 30mm

System Benefits

- Enables Compact and Lightweight Systems
- High Efficiency Operation
- Mitigates Over-voltage Protection
- Reduced Thermal Requirements
- Reduced System Cost

Applications

- Induction Heating
- Motor Drives
- Solar and Wind Inverters
- UPS and SMPS
- Traction

Part Number	Package	Marking
CAS300M12BM2	Half-Bridge Module	CAS300M12BM2

Maximum Ratings (T_c = 25˚C unless otherwise specified)

Symbol	Parameter	Value	Unit	Test Conditions	Notes
V_{DSmax}	Drain - Source Voltage	1.2	kV		
V_{GSmax}	Gate - Source Voltage	-10/+25	V	Absolute Maximum values	
V_{GSop}	Gate - Source Voltage	-5/20	V	Recommended Operational Values	
I_D	Continuous Drain Current	404	A	V_{GS} = 20 V, T_C = 25 ˚C	Fig. 24
		285		V_{GS} = 20 V, T_C = 90 ˚C	
$I_{D(pulse)}$	Pulsed Drain Current	1500	A	Pulse width t_P = 200 μs Repetition rate limited by T_{jmax}, T_C = 25˚C	
T_{Jmax}	Junction Temperature	150	˚C		
T_C, T_{STG}	Case and Storage Temperature Range	-40 to +125	˚C		
V_{isol}	Case Isolation Voltage	4.0	kV	AC, 50 Hz , 1 min	
L_{Stray}	Stray Inductance	14	nH	Measured between terminals 2 and 3	
P_D	Power Dissipation	1660	W	T_C = 25 ˚C, T_J = 150 ˚C	Fig. 23

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Electrical Characteristics (T_c = 25 °C unless otherwise specified)

Symbol	Parameter	Min.	Typ.	Max.	Unit	Test Conditions	Note
$V_{(BR)DSS}$	Drain - Source Breakdown Voltage	1.2			kV	V_{GS} = 0 V, I_D = 1 mA	
$V_{GS(th)}$	Gate Threshold Voltage	1.8	2.3		V	V_{DS} = 10 V, I_D = 15 mA	Fig 7
I_{DSS}	Zero Gate Voltage Drain Current		500	2000	μA	V_{DS} = 1.2 kV, V_{GS} = 0V	
			1000			V_{DS} = 1.2 kV, V_{GS} = 0V, T_J = 150 °C	
I_{GSS}	Gate-Source Leakage Current		1	100	nA	V_{GS} = 20 V, V_{DS} = 0V	
$R_{DS(on)}$	On State Resistance		5.0	5.7	mΩ	V_{GS} = 20 V, I_{DS} = 300 A	Fig. 4, 5, 6
			8.6	9.8		V_{GS} = 20 V, I_{DS} = 300 A, T_J = 150 °C	
g_{fs}	Transconductance		94.8		S	V_{DS} = 20 V, I_{DS} = 300 A	Fig. 8
			93.3			V_{DS} = 20 V, I_D = 300 A, T_J = 150 °C	
C_{iss}	Input Capacitance		11.7		nF	V_{DS} = 600 V, f = 200 kHz, V_{AC} = 25 mV	Fig. 16, 17
C_{oss}	Output Capacitance		2.55				
C_{rss}	Reverse Transfer Capacitance		0.07				
E_{on}	Turn-On Switching Energy		6.05		mJ	V_{DD} = 600 V, V_{GS} = -5V/+20V I_D = 300 A, $R_{G(ext)}$ = 2.5 Ω Note: IEC 60747-8-4 Definitions	Fig. 19, 20
E_{off}	Turn-Off Switching Energy		5.95		mJ		
$R_{G(int)}$	Internal Gate Resistance		3.0		Ω	f = 200 kHz, V_{AC} = 25 mV	
Q_{GS}	Gate-Source Charge		166		nC	V_{DD}= 800 V, V_{GS} = -5V/+20V, I_D= 300 A, Per JEDEC24 pg 27	Fig. 15
Q_{GD}	Gate-Drain Charge		475				
Q_G	Total Gate Charge		1025				
$t_{d(on)}$	Turn-on delay time		76		ns	V_{DD} = 600V, V_{GS} = -5/+20V, I_D = 300 A, $R_{G(ext)}$ = 2.5 Ω, Timing relative to V_{DS} Note: IEC 60747-8-4, pg 83 Inductive load	Fig. 25
t_r	Rise Time		68		ns		
$t_{d(off)}$	Turn-off delay time		168		ns		
t_f	Fall Time		43		ns		

Free-Wheeling SiC Schottky Diode Characteristics

Symbol	Parameter	Min.	Typ.	Max.	Unit	Test Conditions	Note
V_{SD}	Diode Forward Voltage		1.7	2.0	V	I_S = 300 A, V_{GS} = 0	Fig. 9, 10, 11
			2.2	2.5		I_S = 300 A, T_J = 150 °C, V_{GS} = 0	
Q_C	Total Capacitive Charge		3.2		μC		

Note: The reverse recovery is purely capacitive

Thermal Characteristics

Symbol	Parameter	Min.	Typ.	Max.	Unit	Test Conditions	Note
R_{thJCM}	Thermal Resistance Juction-to-Case for MOSFET		0.070	0.075	°C/W	T_C = 90 °C, P_D = 150 W	Fig. 27, 28
R_{thJCD}	Thermal Resistance Juction-to-Case for Diode		0.073	0.076		T_C = 90 °C, P_D = 130 W	

Additional Module Data

Symbol	Parameter	Max.	Unit	Test Condtion
W	Weight	300	g	
M	Mounting Torque	5	Nm	To heatsink and terminals
	Clearance Distance	12	mm	Terminal to terminal
	Creepage Distance	30	mm	Terminal to terminal
		40	mm	Terminal to baseplate

Typical Performance

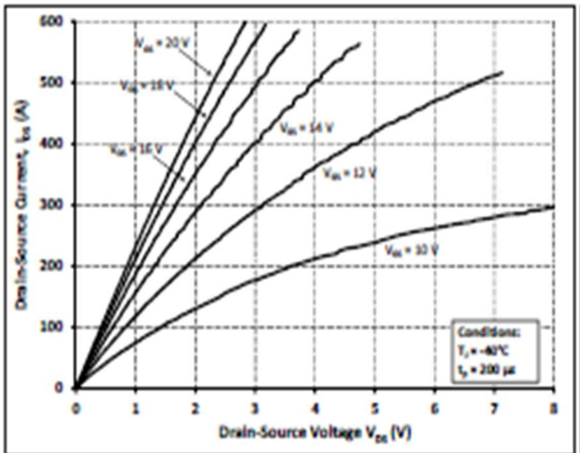

Figure 1. Typical Output Characteristics T_J = -40 °C

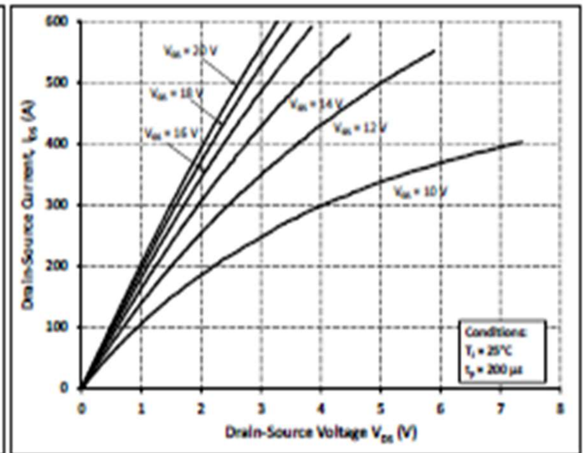

Figure 2. Typical Output Characteristics T_J = 25 °C

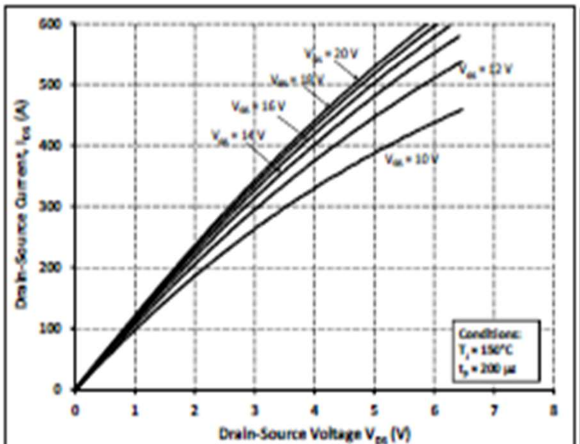

Figure 3. Typical Output Characteristics T_J = 150 °C

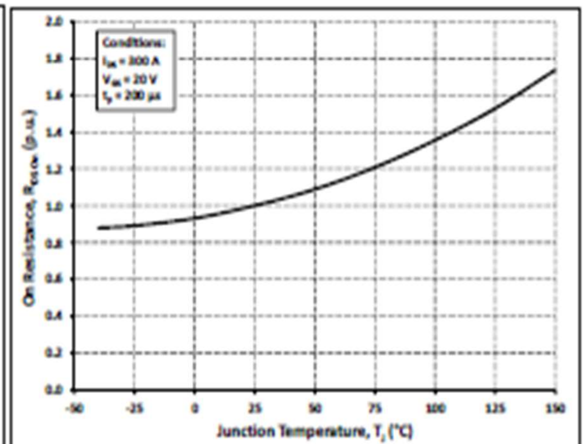

Figure 4. Normalized On-Resistance vs. Temperature

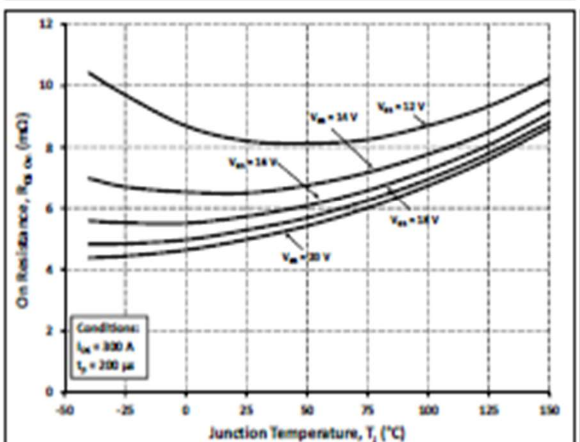

Figure 5. Typical On-Resistance vs. Temperature for Various Gate-Source Voltage

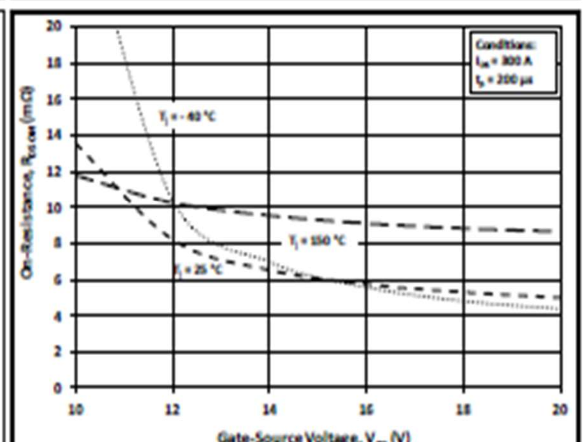

Figure 6. Typical On-Resistance vs. Gate Voltage

Typical Performance

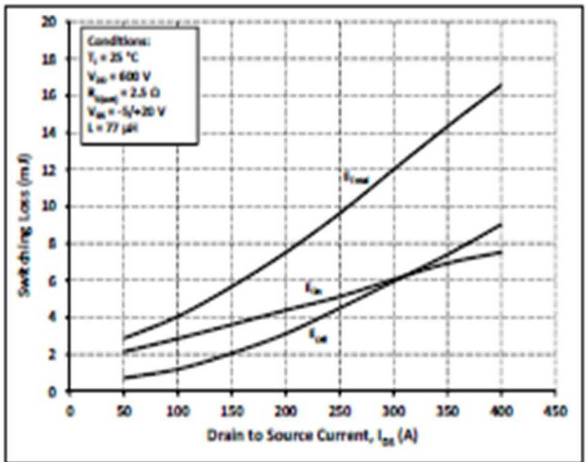

Figure 19. Inductive Switching Energy vs. Drain Current For V_{DS} = 600V, R_G = 2.5 Ω

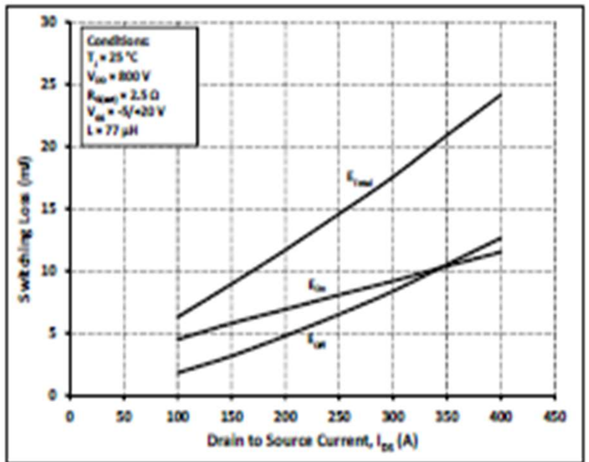

Figure 20. Inductive Switching Energy vs. Drain Current For V_{DS} = 800 V, R_G = 2.5 Ω

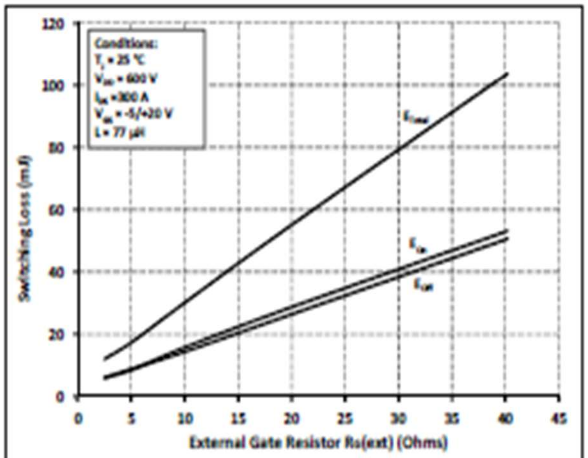

Figure 21. Inductive Switching Energy vs. $R_{G(ext)}$

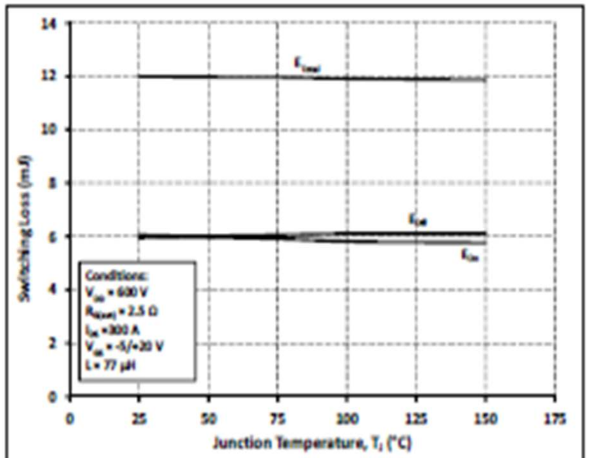

Figure 22. Inductive Switching Energy vs. Temperature

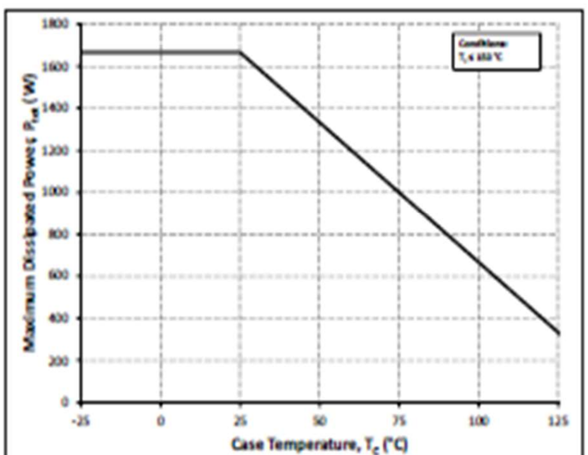

Figure 23. Maximum Power Dissipation (MOSFET) Derating vs Case Temperature

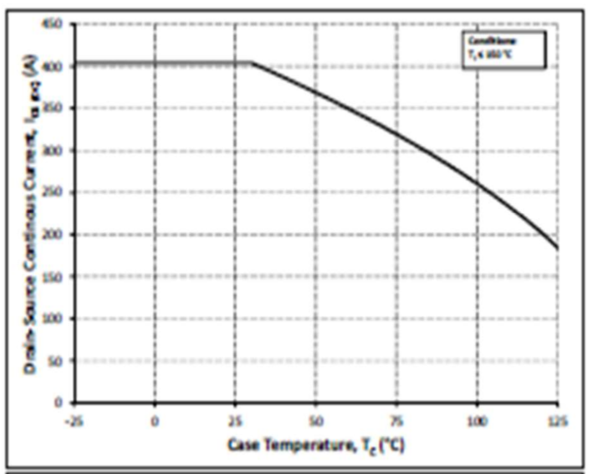

Figure 24. Continous Drain Current Derating vs Case Temperature