RESISTIVE SOLID STATE PROTECTIVE DEVICE

by

Amin Khanlar

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ABSTRACT

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Amin Khanlar

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Under the Supervision of Robert M. Cuzner

This thesis describes and explain different faults to characterize fault specifically for DC distribution systems and DC Microgrids fed by synchronous generators. This will result to a testbed for static and intermittent line-to-line faults, and in future work, various types of ground faults. Automation allows for repeated testing at various voltage levels and precise control over intermittent fault generation. The fault generator is implemented with an IGBT H-bridge topology. Its physical implementation and benefits are described. Experimental results are shown for static line-to-line fault. This testbed will be used to help develop closed form expressions. Once fault currents are characterized and closed form expressions are made, adequate protection systems can be designed. finally, this paper will include simulation and experimental results of line-to-line fault characterization with a DC smoothing capacitor, and intermittent faults of various times.

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Chapter 1 Introduction

The main focus of this thesis is to assess the protection topologies for next generation “breaker” based DC distribution system. Increasing in large scale integration of distributed energy resources and bidirectional power flow requirements, lead to application of DC or AC/DC hybrid microgrid, but instead of many advantages of dc systems there are still some issues which need attention for efficient and reliable performance of the system. Unavailability of zero crossing phenomenon in dc current has made the protection more challenging. Conventional approach of fault detection and protection may not work because of their dependence on voltage droop to ensure tripping of closest relay. Also, the fault current in upstream and downstream look like the same so it’s not suitable for convention relay coordination scheme. Current DC system still employ conventional devices such as AC side circuit breakers which are relatively slow and may result in interruption of power in major part of the grid. In present scenario there is a need of fast acting, high rated and smart protective devices in medium voltage DC (MVDC) protection system.

Background

Recent developments and trends in the electric power consumption clearly indicates an increasing use of DC in end-user equipment. Computers, TVs, and other electronic-based apparatus use low-voltage DC obtained by means of a single-phase rectifier followed by a DC voltage regulator. In factories, the same input stage is used for process-control equipment, while directly-fed ac machines have been replaced by ac drives that include a two-stage conversion

process. By using DC for distribution systems, it would be possible to decrease the amount of energy losses due to energy conversion and moreover, it would be less equipment in the system. Plus, DC energy delivery is characterized by lower losses and line voltage drops in great distances.

Microgrid, which is one of the main foundations of the DC distribution system, inherits many properties of the smart grid such as, self-healing capability, real-time monitoring, advanced two-way communication systems, low voltage ride through capability of Distribution Generation (DG) units, and high penetration of DGs. These substantial changes in properties and capabilities of the future grid result in significant protection challenges such as bidirectional fault current, various levels of fault current under different operating conditions. In addition, necessity of standards for automation system, cyber security issues, as well as absent of zero crossing current and the need for new circuit breakers for DC Microgrids make the development of future technologies for DC microgrid very essential. Due to these new challenges in microgrid protection, the conventional protection strategies have to be either modified or substituted with new ones. The aim of this study is to provide a review of the protection challenges in AC and DC Microgrids and available solutions to deal with them.

For over a century, the conventional structure of power system has been defined based on centralized generation resources interconnected to end-users through long transmission lines. Such a power system has some drawbacks involving high power losses, low penetration of Renewable Energy Sources (RESs), poor visibility, slow response times due to electromechanical devices and lack of sufficient standardization for system automation of

power distribution, particularly for RESs, Energy Storage Systems (ESSs) and Electric Vehicles (EVs). Hence, there is a growing effort to address these issues. DC microgrid is a promising trend for future power system aimed at addressing the aforementioned shortcomings of the existing grid. The salient features of the promising smart grid in comparison with the existing grid are presented in Table I [1],[2]. A microgrid is defined as a part of the grid consisting of Distributed Energy Resources (DERs), Distributed Storages (DSs) and Distributed Loads (DLs), which could operate autonomously or connected to the main grid [3].

Table 1. A comparison of existing Grid and Smart Grid [1], [2]

Existing Grid	Smart Grid
Electromechanical	Digital
One-way Communication	Two-way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Widespread Sensors
Manual Restoration	Self-Healing
Limited Control	Pervasive Control
Failures and Blackouts	Adaptive and Islanding

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Chapter 2 Conventional DC Breaker

2.1 Conventional Protective Relays

For over a century, the conventional transmission and distribution power lines relied on the mechanical/electro-mechanical circuit breakers to protect against faults in the system. This system is defined based on centralized energy generation (turbines, generators, nuclear plants, coal plants etc.). Now a day, by increasing demand for energy, other concepts of energy generation, transmission and distribution are emerging which need different method of protection. Moreover, the transition from AC to DC makes it even more critical to have faster and more reliable circuit breakers.

There are different components in a conventional power system including generators, transmission lines, bus bars, transformers, reactors, capacitors, loads, etc. that based on the type and application of that part, different protection method needs to be performed. All equipment must be protected against various forms of faults.

Current-based, voltage-based, frequency-based or impedance-based methods are among the most well-known protection systems. [3]

Table 2 Different types of protection relays, applications, advantages and disadvantages [7]

Protection type	Application	Advantages	Disadvantages
OC protection	Transmission and distribution lines Generators	Simple inexpensive	Requires additional analysis to discriminate real-fault from other transient phenomena.
Directional OC protection	Transmission and distribution lines. Generators	Good candidate for meshed distribution system.	More expensive than OCR. More complex

		Less expensive than differential protection	coordination process Requires additional analysis to discriminate real-fault from other transient phenomena.
Distance protection	Transmission and distribution lines. Busbars. Generators.	Not influenced by source impedance variations.	High impedance fault, power swing, bidirectional power flow, and high resistance fault can deteriorate the protection performance. More expensive than OCR.
Differential protection	Transmission lines. Busbars. Transformers. Generators.	Relatively simple. High speed and sensitivity. Inherent selectivity. Immune to power swings and external fault. High performance for high impedance fault.	High cost of implementation. Error in measured current and communication delay affect on the protection performance.
Under Voltage (UV),Over Voltage (OV) ,Under Frequency (UF), and Over Frequency (OF)	Islanding detection. Load shedding. Satisfying LVRT requirements.	Proper design of Under Frequency Load Shedding (UFLS) could be an effective tool to prevent power system blackout. • Islanding detection based on UF/OF and UV/OV are cost efficient and have no impact on power quality.	Separate designing of Under Voltage Load Shedding (UVLS) and UFLS protection will not lead to the desired outcome for load shedding purpose. In conventional UFLS, the amount of shed load is fixed and does not affect by disturbance location, bus voltage, and rate of change of frequency drop. Islanding detection based on UF/OF and UV/OV have large Non-Detection

			Zone (NDZ) and thresholds are required to be adjusted properly.

2.1.1 Overcurrent relays

Overcurrent Relays (OCRs) considered as simple and economical protective devices, employed as the main protective relays for distribution and backup protection for transmission systems. Generally, there are three types of time-current characteristics for OCRs: 1) instantaneous; 2) definite time, and 3) inverse-time.

If the current amplitude exceeds a pre-defined value, the relay with instantaneous and definite-time characteristics trips instantly. For the inverse time-current characteristic, operating time is mathematically defined by IEEE C37.112 [8]

2.1.2 Directional OCR

The directional overcurrent relay (DOCR) is one of the alternatives for overcoming the shortcomings of the OCRs in DSs including DGs. DOCRs use voltage reference [9], pre-fault current [10], post-fault current [1] to detect the direction of the fault.

As potential transformer is absent in the distribution system the voltage reference in not applicable in distribution system. On the other hand, although in the second method pre-fault current is utilized for detecting the direction of the fault, this method requires the voltage for the detection of the power-flow direction. Therefore, the third method is a promising solution for detection of the fault

direction.

2.1.3 Distance Relays

Distance relays detect a fault based on measuring the apparent impedance calculated by division of the voltage by the measured current at the relaying point. Then, the apparent impedance is compared with the particular value of impedance called reach point impedance. If it is less than the reach point impedance, it is

assumed that the fault is located between the relay and the reach point; therefore, a trip signal is sent to the respective CB. According to the principle of the distance relay, one of the main advantages of this relay is that the source impedance variations, do not affect the relay performance [3].

2.1.4 Differential Relays

A current differential protective relay first measures the currents flowing in and flowing out the bus, transformer, or transmission line then compares the shared information which are transferred by a pilot wire, fiber optics communication, Power Line Carrier (PLC), or a wireless communication network. If the

difference of the input and output currents exceeds a threshold, a fault is detected in the protected zone [12]. With the rapid increase in communication technology, implementation of the differential protection is less costly. Furthermore, high sensitivity and selectivity, immunity to power swing and external fault, better

performance for high impedance fault, and simplicity are among the main advantages of this relay. Differential relays have the capability to block the protection function for the power

swing. However, if the fault occurs during the power swing, the relay must send a tripping signal to CB. Fault detection during the

power swing will become a challenge when there is a symmetrical fault. In [13], a new method called differential power-based fault detection was proposed to identify symmetrical fault during slow and fast power swing.

2.1.5 UV/OV and UF/OF Protective Relays

Voltage sag usually occurs as a result of the fault, overload, and starting of the large motors [14]. On the other hand, overvoltage takes place due to many reasons such as lightning, switching, disconnection of bulk loads, ferro-resonance, and insulation faults [15], [16]. Recently, it has been recognized that high penetration of photovoltaic (PV) systems at the distribution level could lead to overvoltage caused by reverse power flow [17]. Typically, disturbances in power system disrupt the balance between consumption and generation of active and reactive powers, and as a result, voltage and frequency stability are jeopardized, simultaneously.

Accordingly, OV, UV, OF, and UF protection relays are four other conventional protective relays used to enhance stability in the power system. Voltage and frequency relays have many applications such as passive islanding detection [18], load shedding (LS) [19], [20], and providing Low Voltage Ride Through (LVRT) capability of DG [21].

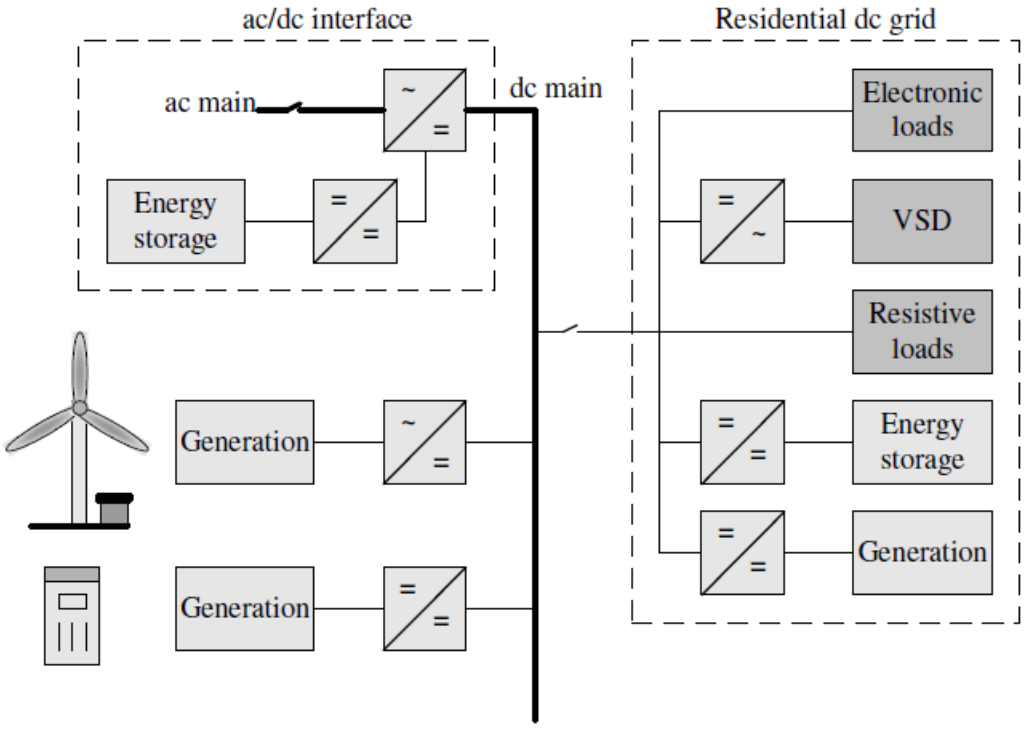

Figure 2.1 layout of low-voltage DC distribution system with CBs

Based on protection technology and component, circuit breakers can be categorized in 4 different types, based on application, hardware and respond time. It is listed below as:

Mechanical DC Circuit Breaker

Static DC Circuit Breaker

Hybrid DC Circuit Breaker

Solid State Circuit Breaker

2.2 Different Circuit Protection Technologies

2.2.1 Mechanical DC Circuit Breaker

At present, a mechanical DC circuit breaker is commonly used as a DC system breaking equipment which is about to transform the AC circuit breaker for breaking into the DC circuit system to achieve the purpose. Since the DC system doesn't exist zero crossing in the current and the arc will be a difficulty. For low voltage and low current systems, we can achieve the purpose of forcing the DC arc by increasing the arc voltage and break-limiting resistor in series or sub-field and control gas power to shutoff etc. However, in term of higher voltage levels and larger short-circuit current system forced extinction is no longer applicable. Hence the need to add an oscillation circuit to form a current zero-crossing and help achieve interrupter breakers off. Oscillation circuit generally consists of the LC resonant circuit, which formed the current zero crossing to cut off mechanical circuit breaker and cooperate with the corresponding energy absorption circuit to absorb the circuit energy which stored in the energy storage element. [4]

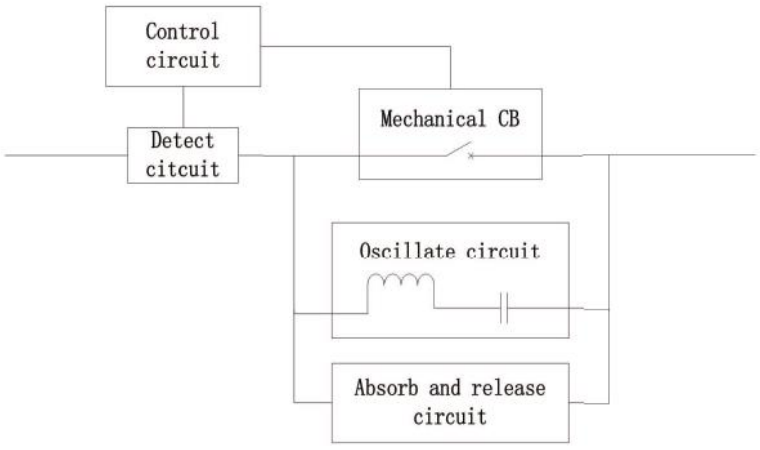

Figure 1.2 Basic Structure of mechanical DC circuit breaker [4]

2.2.2Static DC Circuit Breaker

Static circuit breaker is a circuit breaker which means no mechanical moving parts and fully completed the circuit breaker off and closing process by Semiconductor devices. With the emergence and development of power electronic devices in the later 1970s, there appeared thyristor (SCR) of the circuit breaker as a switching element. The birth of the whole controller parts contributes to rapid development of static circuit breaker in 1980s to the 1990s.Static circuit breaker has the following character: breaking fast, no arc, no sound, nothing to break the dead zone, long life, high reliability work for speed and mobility requirements of the occasion. Its structure is shown in Figure 2. Compared with the mechanical circuit breakers, switching speed of static circuit breakers gets greatly improved and the switching time can be accurately controlled. Although static circuit breaker with higher costs compared to the mechanical breaker, but because of its excellent performance, and the continuous development of power electronics technology, static circuit breaker in the DC system has got more and more attention.

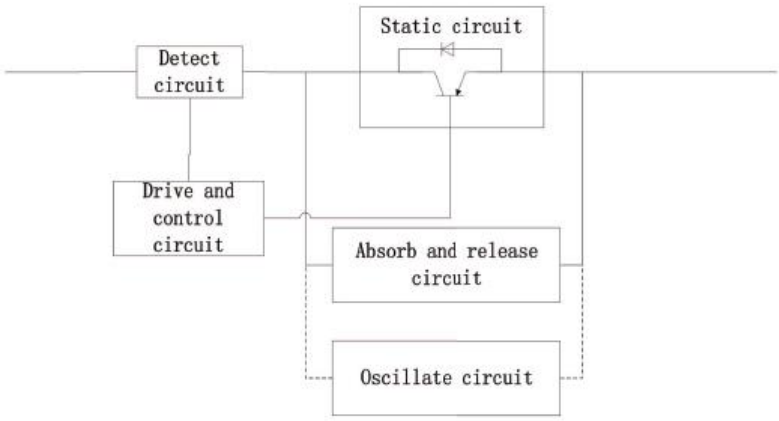

Figure2.2 Basic structure of static DC Circuit Breaker [4]

2.2.3 Hybrid Circuit Breaker

The emergence of mechanical switches and power electronic devices combined to constitute a hybrid circuit breaker in 1990s. Combining the two type DC circuit breaker will get good mechanical switch static characteristics and good dynamic performance. The structure is shown in Figure 3. From a theoretical perspective, the hybrid DC circuit breaker is an ideal DC circuit breaker which combines advantages of mechanical and solid-state circuit breaker and overcoming the drawbacks of both. It has small conduction loss, breaks in a short time, regardless of off the dead zone, long life, high reliability, no special cooling equipment. It is the new direction of research and development of circuit breakers which can be used in engineer application.

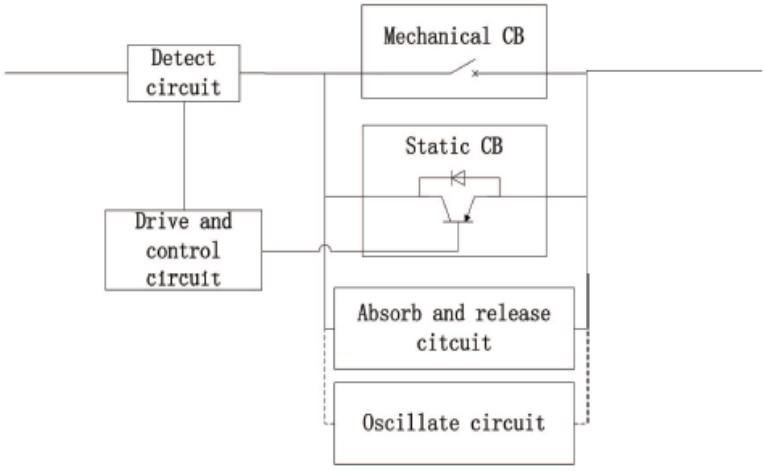

Figure 2.3 Basic structure of Hybrid Mechanical-Static DC Circuit Breaker [4]

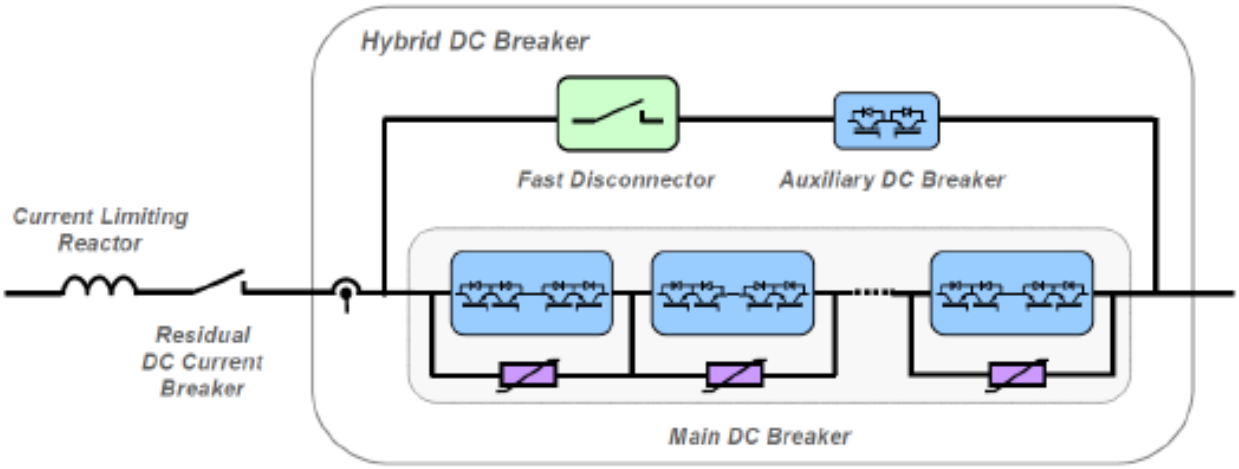

figure 2- 1 Circuit schematic for ABB's hybrid HVDC circuit breaker [22]

2.2.4 Solid State Circuit Breaker (SSCB)

SSCBs use semiconductor devices to provide the power for switching, replacing the hard contacts in convenient Electro-Mechanical circuit breakers.

Its circuitry responds very fast to the command signal and interrupt fault as needed and can be combined with different variety of control mechanism which gives a huge advantage over older breakers. SSCB devices can switch ON/OFF with small external voltage across control terminal (usually called Gate). Operation region usually dictated by the design and application and may vary from device to device even with the same topology.

There are different mature component-based technologies for SSCB such as:

I) BJT

II) IGBT

III) IGCT

IV) MOSFET

V) GTO Thyristor

VI) SCR

VII) SiC

Other mature devices such as Bipolar Junction Power Transistors (BJTs) could be used for SSCBs, but this is somewhat impractical because they have low current gain, limited current capability, and are subject to second breakdown, particularly during device turn-off. Because of the BJTs limited current capability, many
devices need to be paralleled to handle the large amounts of current to be carried by SSCBs. BJTs are not easy to operate in parallel, but some high-gain, high current Darlington BJT modules do exist. [1]

Unfortunately, most of these devices have been phased out of production, as the newer Insulated Gate Bipolar Transistor (IGBT) modules have largely replaced them. The newer Metal Oxide Field-Effect Transistor (MOSFET) device solves the problems of low current gain and second breakdown, but has limited current capability, unless many devices are connected in parallel. The MOSFET is a voltage-controlled device, rather than a current-controlled device like the BJT, so its gate current requirements are less and its gate-drive circuit can be relatively simple.

Even though MOSFETs are easily operated in parallel, there are very few high current MOSFET modules presently available. The MOSFET has a very high switching capability, but its voltage ratings are presently limited to the 1000– 1200-volt range. Because of its relatively

high on-state resistance, the MOSFET has a relatively high on-state voltage drop, which results in high power losses at high

currents, particularly for the higher voltage devices. The newer IGBT device, which is basically an improved type of power transistor with many MOSFET type characteristics, provides high gain and eliminates the problem of second breakdown. Like the MOSFET, the IGBT has limited current capability, unless several devices are put in parallel. Paralleling of many IGBTs is performed quite well in the high-current modules that are now available and modules can be successfully paralleled. The IGBT also has the advantage of relatively fast switching and high voltage capability. Like the MOSFET, the IGBT has the

advantage of being a voltage-controlled device, so its gate current requirements are much less than those of the BJT or the Darlington BJT module. All of these features make IGBT-based SSCBs quite practical, especially in low and medium current ratings. [2]

The gate turn-off Thyristor is a PN device can be turned like an ordinary thyristor by a pulse of Positive gate current. It can be easily turned off by a negative gate pulse of approximate amplitude. As no forced commutation circuitry is required for GTOs. These devices are compact and less cost.

GTO require a negative high current Pulse in order to turn off. The latching current for large power GTOs is several amperes as compared to 100-500mA for conventional thyristors of the same rating. If Gate current is not able to turn on the GTO, it behaves like a high voltage low gain transistor with considerable anode current.

Table 3. Different SSCB parameters [1]

Parameter	Infineon FZ2400R17KE3 IGBT[a]	ABB 5SHY35L4512 IGCT[b]	ABB 5SGA06D4502 GTO
Peak Voltage	1700 V	2800 V	2800 V
On-State Voltage	2.23 V@ 2100A	1.67V@2100A	4 @ 600 A
$I_{continuous}$	2400 A	2100 A	
$I_{interrruption}$	4800 A	4000 A	
I_{TSM} surge current	9.2 Ka for 10 usec	35 kA for 10 msec	6 kA for 1 ms
I^2t energy capability	423 A^2	6.1 MA^2	45 kA^2
T_{off} Turn-Off Time	1.89 usec	11usec	5 usec
E_{off} Turn-Off losses	0.91 joule	26 joules	1.9 joules
Total Silicon Area	40.6 cm^2	56.7 cm^2	
R_{JC} Thermal Resistance	0.010 C/W	0.0085 C/W	0.085 C/W (SSC) 0.005 C/W (DSC)
Creepage Distance	32 mm (1.26 in.)	33mm (1.3 in.)	30 mm
Double-sided cooled	No	Yes	Yes
Integrated Gate-Drive	Add on gate-drive	Yes	Yes

	PWA available		
Fiberoptic Interface	No	Yes	NA

a. Website: www.infineon.com.

b. Website: www.abb.com/semiconductors.

SiC can be a good choice for SSPD but there is one major limitation for SiC chip. The SiC wafer size is smaller than others but this compensated with higher operating temperature (which is a reasonable approach in power conversion applications). This smaller size wafer limits the amount of current that is allowed to pass through the device which plays a big role (even for a very brief time) in SSPD application. [22]

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Chapter 3 DC Fault Characterization

The direct current distribution is a promising solution for future needs of energy. It can be used for a transportation, EVs, trains, ships or aircrafts. Combining this with the increasing demand for energy, DC distribution systems can be easily integrated with storage-energy (DES) units as well as renewable energy resources (DERs).

When coming to a short circuit, the process of cutting off the current and opening is similar to the common opening process. When the detection circuitry detects a short-circuit fault, the drive control circuit sends a close signal to the static switch part and issues a signal to the switch to make the short circuit fault cleared. Because the short circuit occurs (which causes the current continues to increase during operation and cutting short) circuit current is much larger than normal operating current. [1]

Because of the number of reasons such as:

- Lack of zero crossing in DC
- Fast propagation of fault through DERs and integrated sources
- Due to integration of multiple power sources and loads through common DC link, Bidirectional power flow schemes can make fault detection very difficult compare to conventional unidirectional power flow.
- Looped and meshed network topology leads to more complex fault current path.
- Normal impedance-based protection scheme will not work in DC systems.

Finding and isolating fault should be very quick and accurate to prevent major blackout and damage to subsystems and loads.

Increasing the DC bus voltage up to 35kV makes it possible to avoid high current during normal operation but will cause excessive amount of current when rail to rail fault happens. in figure 3.1 below, shown the circuit breaker trip window for up and downstream. Fault propagation in DC system is considerable.

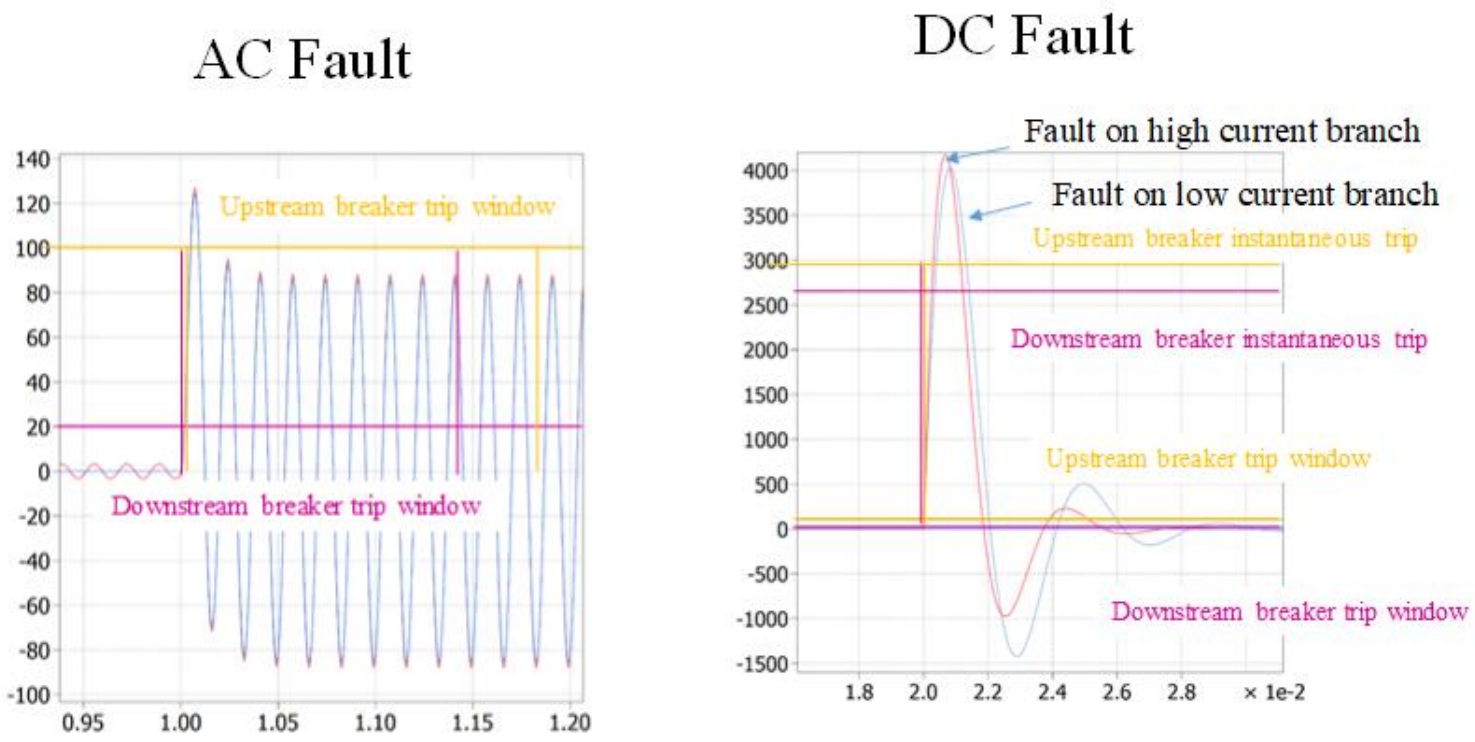

Figure 3.1 AC Vs. DC fault circuit breaker respond window

- Circuit breaker only has a few micro seconds to interrupt the increasing fault current.
- In a radial system: circuit breakers should identify the fault location and isolate it respectively.

- In a mesh system: a high-speed communication between circuit breakers and high-speed sensors provide data for the embedded intelligent controller.

3.1 DC distribution system protection

3.1.1 Unit Base protection

A conventional way to protect DC systems (generators, converters and loads) was to put CBs at the input and output of the converter units in order to provide unit base protection for every device.

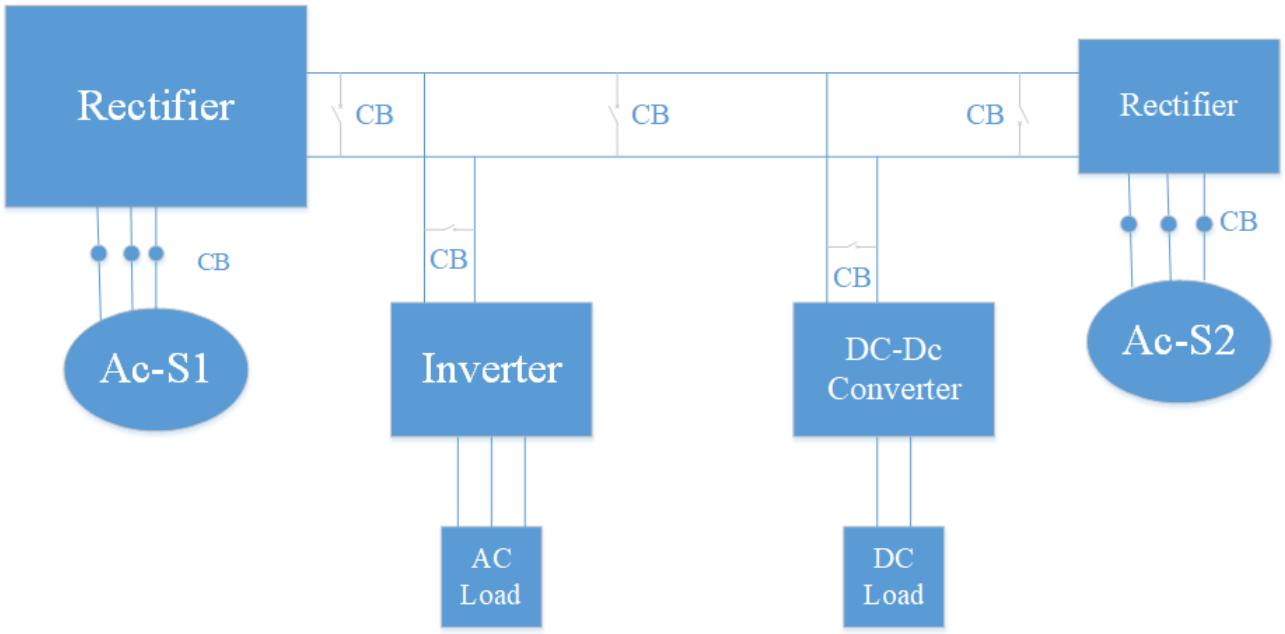

Figure 3.2 Conventional DC unit protection

The alternative approach is to use the converter itself to interrupt the fault by limiting the amount of fault current passing through it (current limiter CB). [6] for example, most VSCs have over current controller on the switches to protect the semiconductor and detects and notify the device controller of an unusual situation. for instance, when current gets too high (and close

to the switch limit) or high $\frac{d_i}{d_t}$ is detected (which is a very common sign of fault current), a signal will send to the controller by switch gate drive and from there controller decides what action should be performed base on the algorithm. This is one way to protect power switches and against over current situation.

3.1.2 Zone Base Protection:

This type of protection usually combined by unit base protection to provide stability and reliability to the system. ZBP implemented by CBs that define zones of protection. The type of CBs is different from zone-to-zone according to the application and importance of that zone to the whole system.

Figure below explain the idea of zonal and unit protection

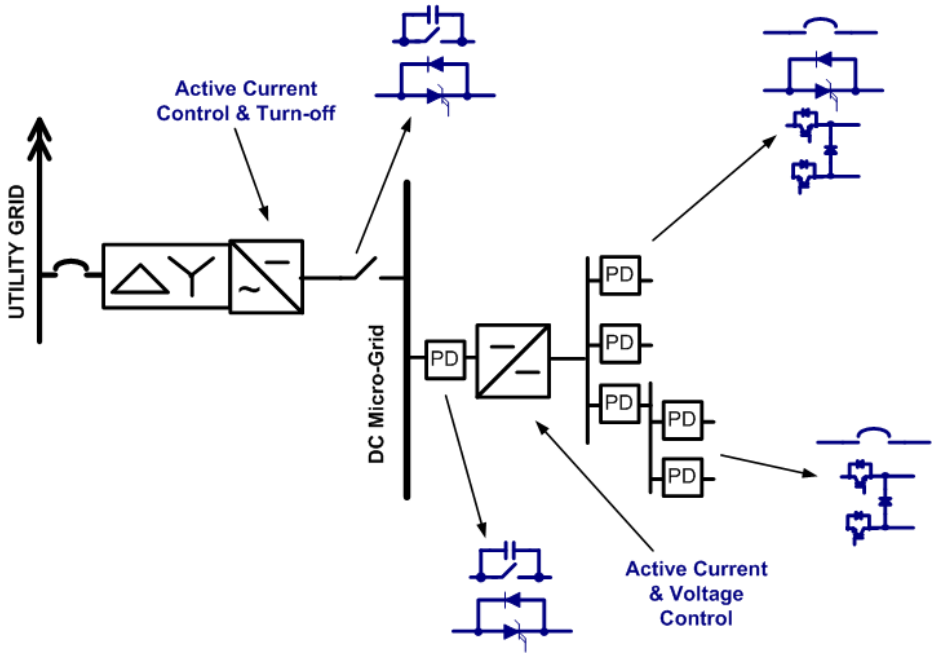

Figure 3.3 Unit and zonal protection in grid tie connection system

3.2 Types of fault in DC systems

DC systems are being more popular during the last decades for an emerging technology for efficient and smart power distribution. However, the development of DC systems requires solving different challenges like protection and power quality issues. [1]

In this thesis term “fault” refers to a short circuit within the system unless other types of fault mentioned. A short circuit fault is considered a true short circuit. The analysis will usually specify the cable impedance between the two points where the fault is occurring. To have better analysis, a different point of view for faults is suggested. For the purposes of this study new definitions of these faults are developed for DC systems in the following sub-sections. [2]

3.2.1 Line to Line fault

L-L fault is represented in Figure 3-1. This figure shows also that a L-L fault can occur from Positive to Negative (PN) or Negative to Positive (NP). This substitution will be more essential, when the DC distribution line includes diodes. Diodes prevent negative current; therefore, PN or NP faults that span positive and negative lines at various parts of the system have the potential of significantly increasing DC voltage stresses in the system.

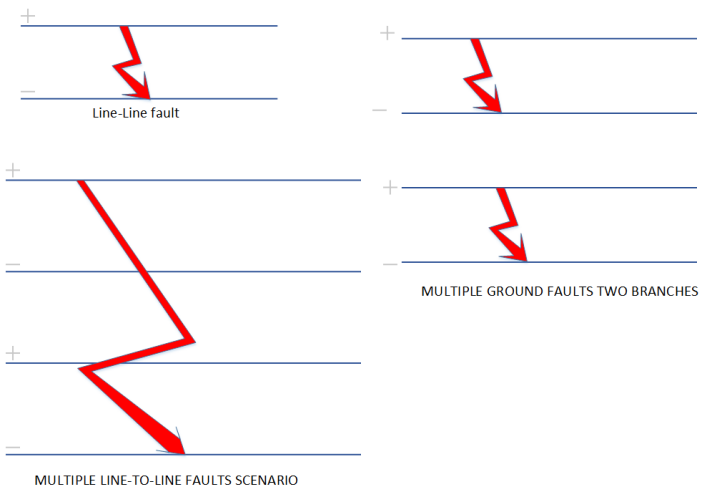

Figure 3.4 DC L-L fault and multiple L-L fault

In the figure multiple fault scenario shown based on a system fed by a Synchronous generator and 6-pulse diode rectifier used to get a DC voltage to feed DER and loads.

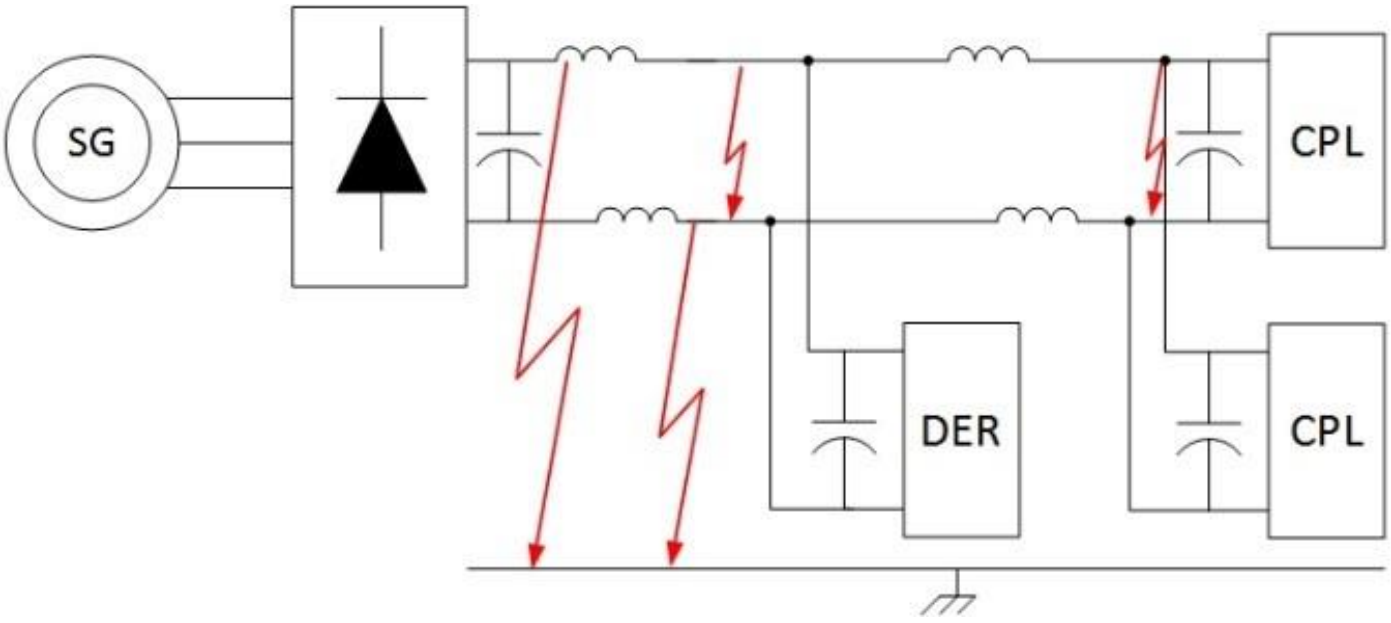

Figure 3.5 Various line-to-line and line-to-ground faults scenarios

VSC DC systems are helpless against these DC faults because IGBTs are blocked for self-protection during the fault, leaving freewheel diodes subject to overcurrent. Thus, VSC DC system behavior during faults must be examined and simulated for an effective system protection design. Additionally, analytical models for the characterization of cable faults in VSC DC systems are needed. [3]

3.2.2 Line-to-Ground fault

L-G fault happens either between Negative pole to Ground (NG) or Positive pole to Ground (PG) or in some rare cases, both poles hit the ground simultaneously (PNG). When PG or NG happens, it will shift the other bus voltage by half the bus to ground voltage.

	I_0	(kA)	-0.063		
R_x	(Ω/km)	0.12	C	(mF)	10
L_x	(mH/km)	0.56	x	(km)	1

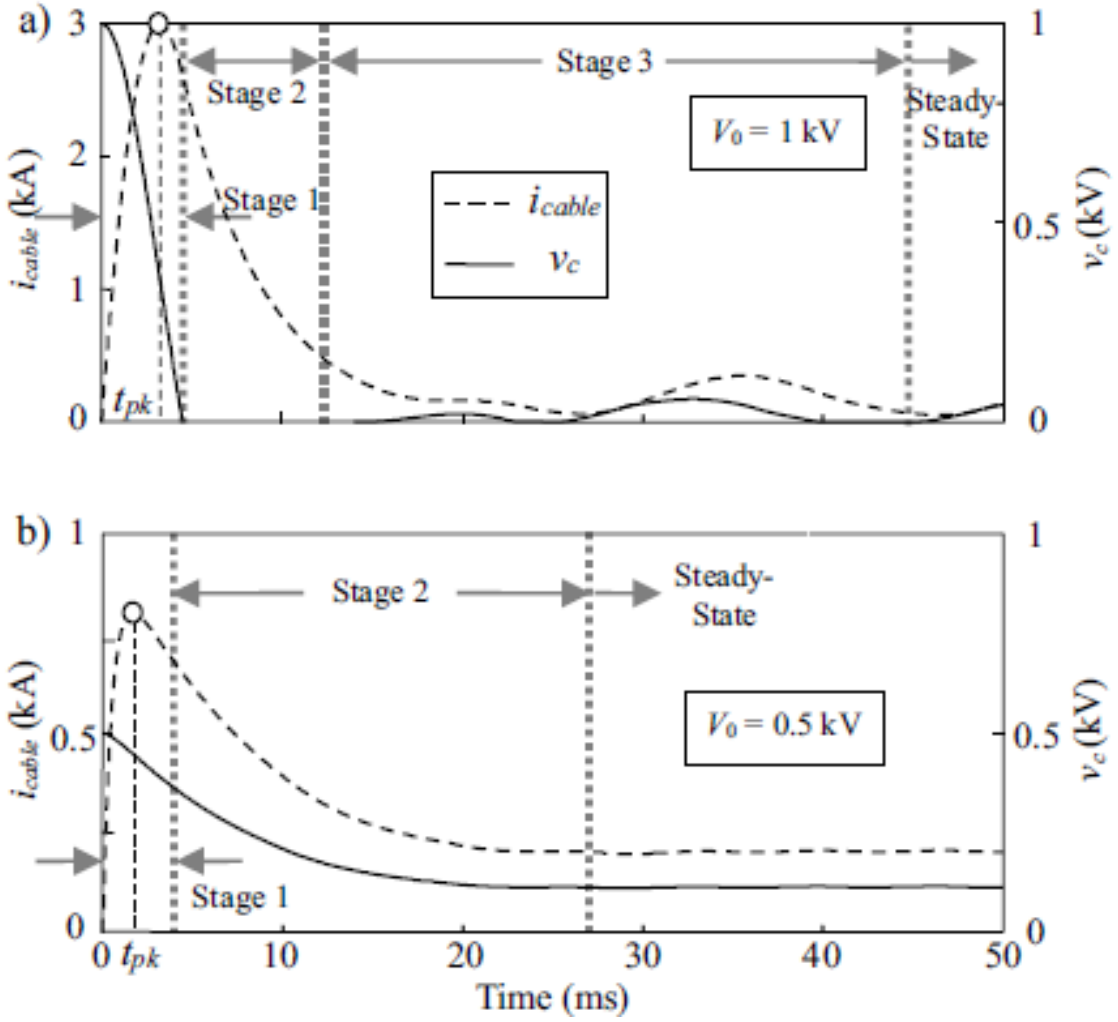

Figure 3.6 simulation of DC cable faults in VSC DC systems: a) pole-to-pole short circuit (R_f=0Ω) Pole-to-ground short circuit (R_f=0.5Ω) [3]

3.3 Mathematical expression of DC fault (Line-Line fault) fed by a synchronous generator

The use of 6-pulse diode rectifier helps to simplify the DC fault calculations as much as possible. In this case it is possible to remove the influence of the transient of the converter control algorithm. the lack of control in such converters makes the determination of the short-

circuit current relevant for the DC system, being impossible to interrupt/control the fault current using the converter. Finally, common AC/DC converters architectures employ reverse diodes to protect the power electronics switches, thus originating a diode bridge rectifier topology during a line-to-line fault. [4]

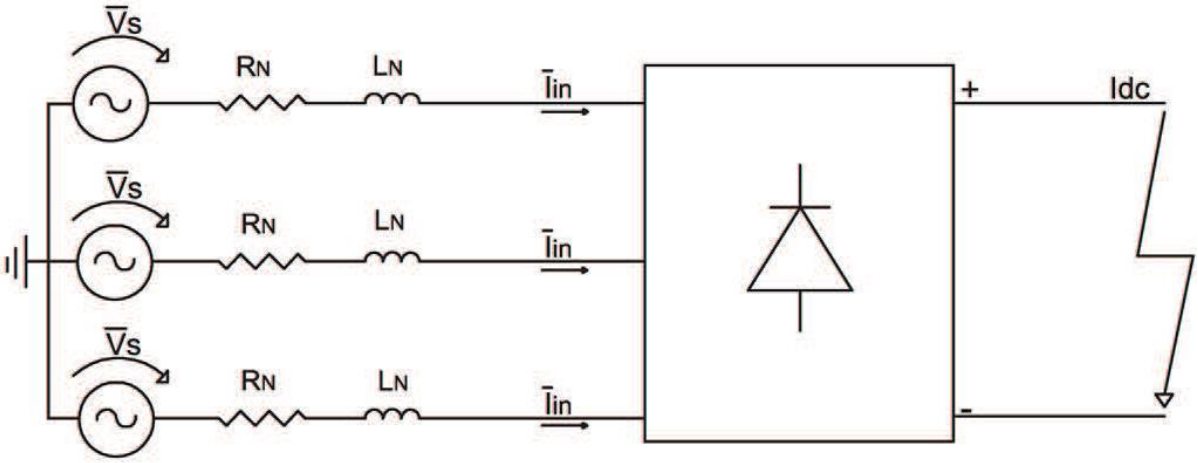

Figure 3.7 3 phase AC/DC fault [8]

There are some considerations such that helps to get clear understanding of fault itself. First, there is no transformer in the system so any effect regarding the transformer is omitted. Second, the distance between generator and diode rectifier is short compare to distribution systems (the longer the distance, the greater the fault current can be). Due to these facts it is possible to estimate the only impedance in the model is the internal impedance of the generator.

The same consideration results in removal of impedance and reactance on the DC

side. As a result, the short circuit DC current hypothetically, is higher than a real one [5].

3.3.1 DQ-Transformation model

The simplified DQ transformation approach applies to AC/DC systems and makes it easier to analyze. This model is focused on finding the DC pole-to-pole short circuit current effect to the 3 phase AC source like the system figure 3-4 and simplified it into figure below (figure 3-5). In this case, the AC side shows the behavior like it is in series with a couple of diodes connected in an inverse parallel configuration [5].

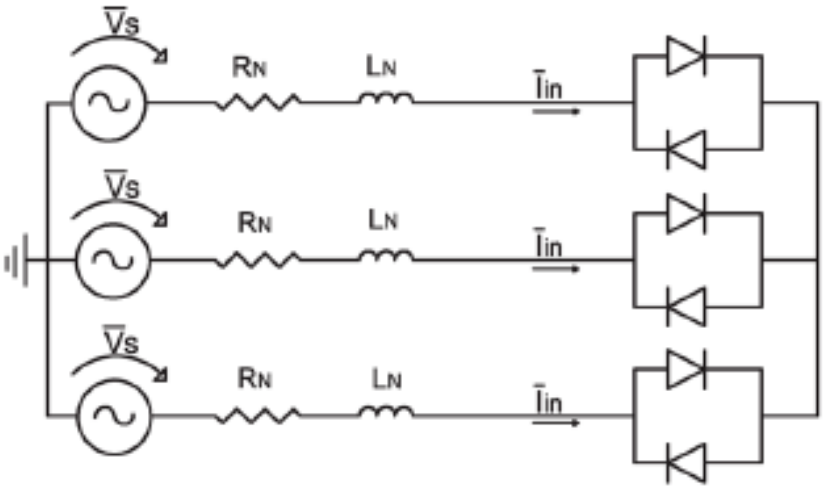

Figure 3.8 Simplified figure using DQ transformation during pole-to-pole short circuit [5]

With all proper simplifications and considering reference angle, the DC short circuit current can be obtained as below:

$$I_{dc} = \frac{1}{Sdq} * \sqrt{2}\, Vo[\frac{1}{X_d} + (\frac{1}{X"_d} - \frac{1}{X'_d})\, e^{\frac{t}{T''_d}} + (\frac{1}{X'_d} - \frac{1}{X_d})\, e^{-\frac{t}{T'_d}})) - (\frac{1}{X"_d})\, e^{\frac{t}{T_{ac}}} . \cos(\omega t)]$$

(1)

$$i_q = v_o \left(\frac{1}{X"_q}\right) e^{\frac{t}{T_{ac}}} \sin(wt) \quad (2)$$

Where:

V_o = constant internal emf rms value, set equal to 1 p.u

X_d , X'_d and $X"_d$ are the characteristic reactance of the synchronous machine

T_d , T'_d are characteristic time constants of synchronous generator

$T_{ac} = \frac{X"d}{w.r_d}$ is the synchronous generator armature short-circuit time constant

$Sdq = \frac{2\sqrt{3}}{\pi}$ is the DQ transformation ratio [5]

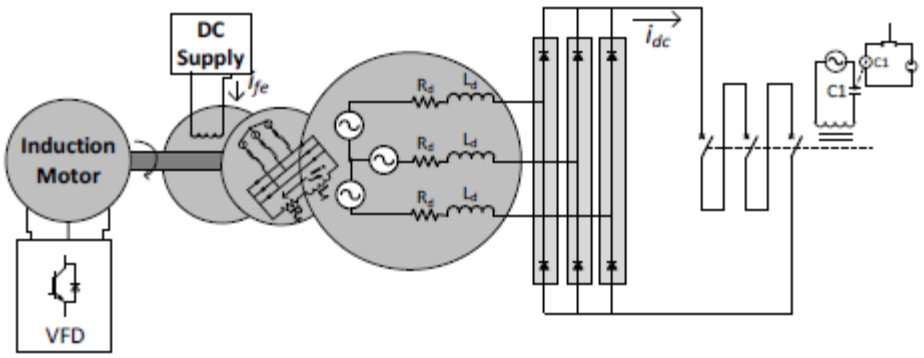

Figure 3.9 short circuit test set up schematic [5].

Table 4 short circuit related parameters [5]

Parameter	*Symbol*	*Value*
Rated volt-Amperes	S_{Rated}	75 KVA
RMS Rated Voltage/Base Voltage	V_{Rated}/V_b	480 V/277 V
RMS Rated Current/Base Current	*Irated/Ib*	90.2 A / 90.2 A
Operating frequency of tests	*f*	60 Hz
Base Impedance	*Zbase*	3.07 W
Stator resistance	*rd*	0.026 p.u
Unsaturated d-axis reactance	*xd (unsat)*	1.656 p.u.
d-axis reactance at 408 Vrms	*xd*	1.38 p.u.
d-axis transient reactance	*x'd*	0.18 p.u.
d-axis sub-transient reactance	*x"d*	0.072 p.u.
q-axis reactance	*xq*	1.328 p.u.
q-axis sub-transient	*x"q*	0.072 p.u.

reactance		
Armature short-circuit time constant	*Tac*	0.00736 s
d-axis transient time constant	*T'd*	0.088 s
d-axis sub-transient time constant	*T''d*	0.016
q-axis sub-transient time constant	*T''q*	0.0002

The detailed information about the simulation and set up test can be find in article [5] Robert Cuzner, Vikas Singh Dept. of Electrical Engineering University of Wisconsin-Milwaukee Milwaukee, WI. Andrea Vicenzutti, Giorgio Sulligoi Dept. of Engineering and Architecture University of Trieste Trieste, Italy, "Simplified Analytical Modeling and Experimental Validation of Diode Bridge Rectifier Operation during Rail-to-Rail Short-Circuit Faults in Synchronous Generator-Fed DC Distribution Systems"

References

[1] O. Oñederra, H. Odriozola, E. Planas, I. López, and V. López, “Overview of DC technology – Energy conversion,” in *Proceedings of the 11th EA4EPQ International Conference on Renewable Energies and Power Quality (ICREPQ’13)*, Bilbao, Spain, 2013, paper 396, pp. 1-6.

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[4] Robert Cuzner, Vikas Singh, Dept. of Electrical Engineering University of Wisconsin-Milwaukee, Andrea Vicenzutti, Giorgio Sulligoi Dept. of Engineering and Architecture University of Trieste, “Simplified Analytical Modeling and Experimental Validation of Diode Bridge Rectifier Operation during Rail-to-Rail Short-Circuit Faults in Synchronous Generator-Fed DC Distribution Systems”

[5] Robert Cuzner, Vikas Singh Dept. of Electrical Engineering University of Wisconsin-Milwaukee Milwaukee, WI. Andrea Vicenzutti, Giorgio Sulligoi Dept. of Engineering and Architecture University of Trieste Trieste, Italy, “Simplified Analytical Modeling and Experimental Validation of Diode Bridge Rectifier Operation during Rail-to-Rail Short-Circuit Faults in Synchronous Generator-Fed DC Distribution Systems”

[6] N. R. Mahajan, “System protection for PEBB based dc distribution systems,” Ph.D. dissertation, Dept. Elect. Comput. Eng., North Carolina State Univ., Raleigh, NC, Nov. 2004

Chapter 4. Topology assessment and hardware consideration for MVDC application

Technically, handling a short circuit situation is tied closely to the location of short circuit (downstream, upstream, etc.) and the type of the short circuit (pole-to-pole, pole-to-ground). This is somehow true for AC grid connected system but for DC grid-connected systems, the number of DERs, DESs and the distribution line topology play important roles to define how protective measures should apply to have a reliable and fault-tolerant system.

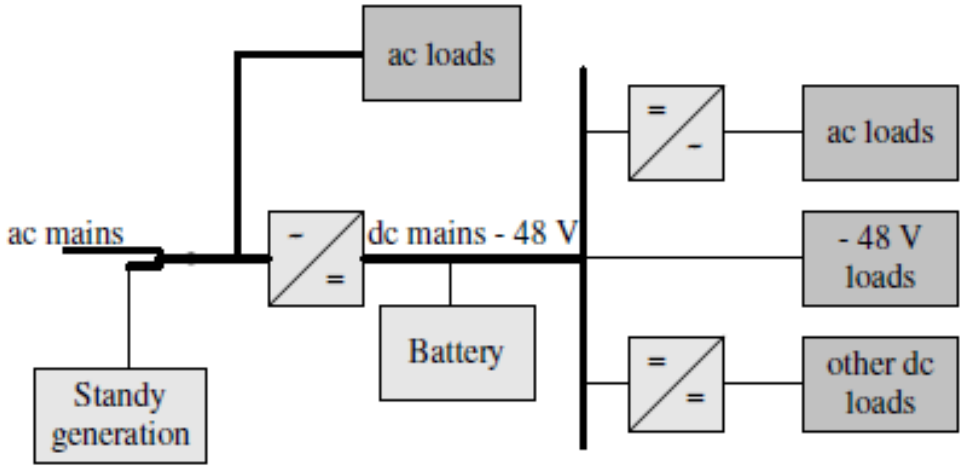


Figure 4.1 layout of a simple distribution system [1].

4.1 Different SSPD categories

There are 3 general categories for SSPD based on fault mitigation techniques:

- Interrupting topology
- Limiting topology

- Dissipating topology

4.1.1 Interrupting topology

In this topology which is shown in fig. 4.1 the main purpose is to prevent the fault current to ramp up so high as soon as possible. Based on this topology each pole should have its own protection device so in case of multi pole-to-pole fault (which is not very uncommon), the system stays protected and fault can't wide spread into the system.

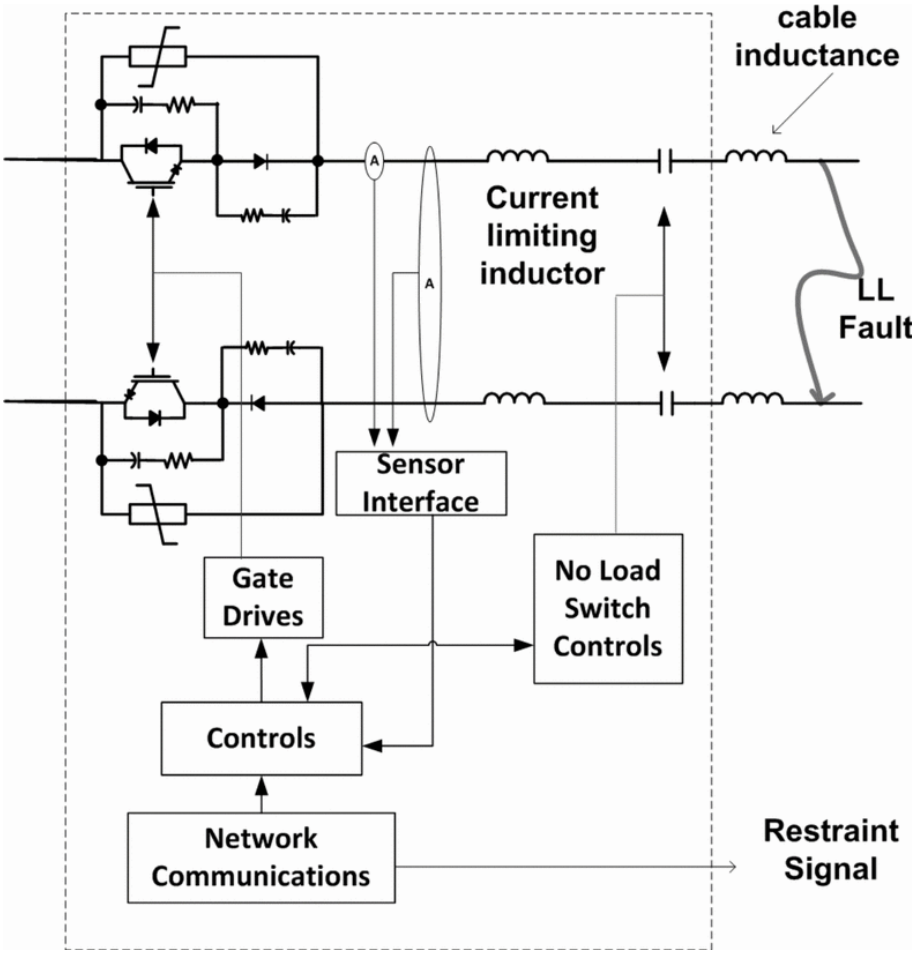


Figure 4.2 interrupting SSPD [2]

4.1.2 Limiting topology

In this topology the current flow measures actively and when the high ratio of d_i/d_t observes, a signal will send to the controller and based on the algorithm a controlling circuit will engage and limit the current flow until it gets to the safe level.

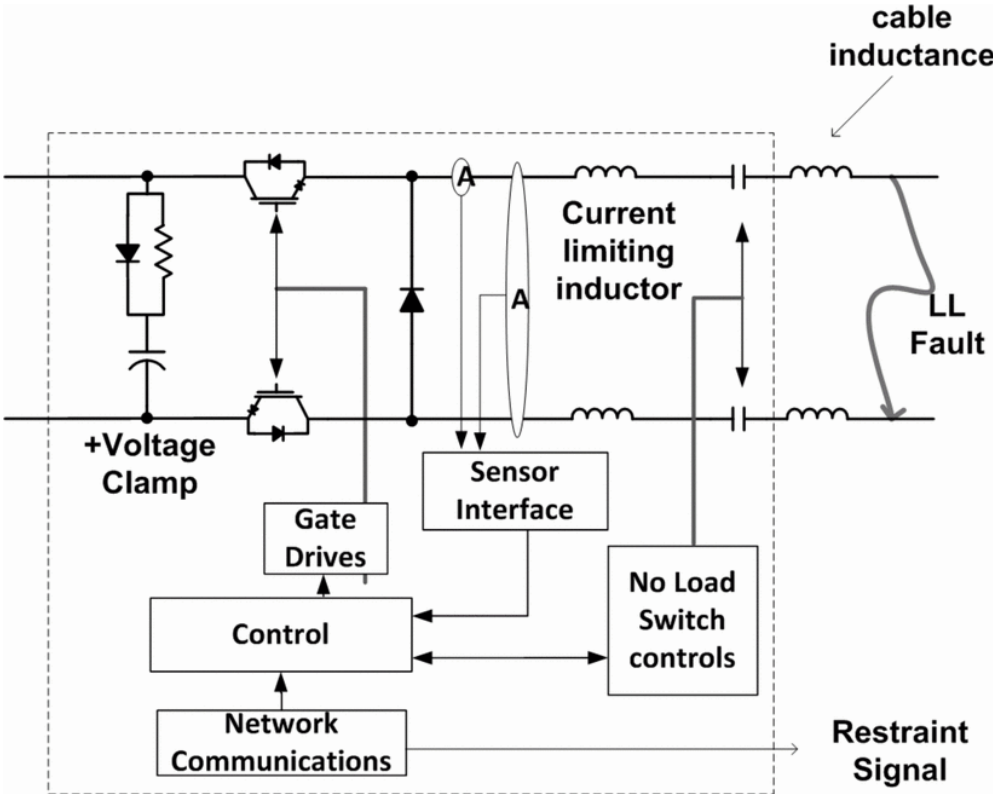


Figure 4.3 Limiting SSPD [2]

4.1.3 Dissipating topology

In this technique, additional devices utilize to divert energy to dissipating components. In this case, a few cautions and considerations should apply to prevent failure. Since cable length is limited in most applications, sizing of resistor and capacitor accurately as important parts of the dissipating process is possible. (figure 4.3)

This design has big benefits. It shares current between two H-bridge legs, so each switch gets half current during fault to mitigate internal device stress [2]. It helps to sustain larger fault current with smaller rating switches instead of having higher current rating and more expensive switches. Another benefit of this topology is that it is scalable. By this it means this system is easily stack up for different power ratings, from low voltage (300V- 1.5 KV) to medium voltage (4 KV-30 KV). This gives a huge benefit to the designer and can easily save a lot of money and time.

Here is the simplified form of the breaker in below.

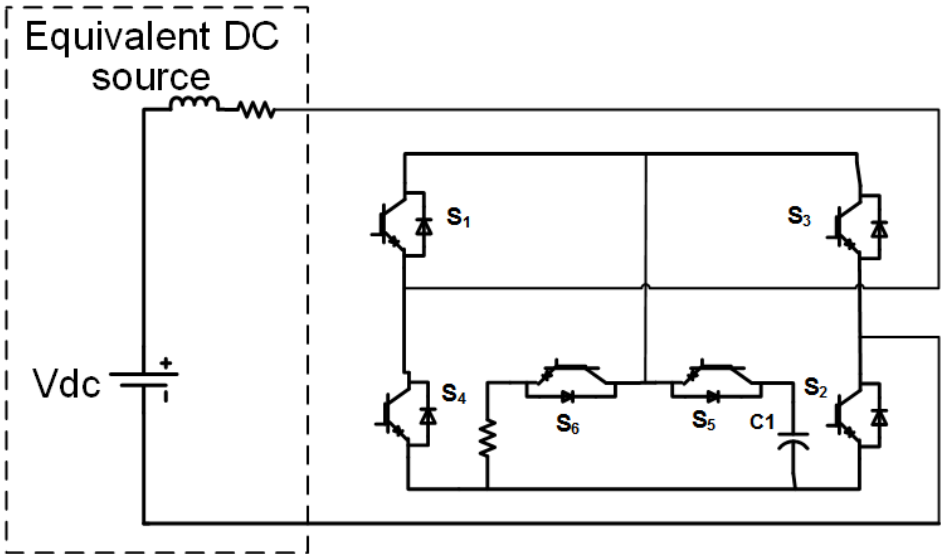


Figure 4.4 dissipating SSPD [2]

In this topology, components like mid-leg capacitor and resistor should follow certain criteria to get the best result in fault situation for instance, mid leg capacitor pre-charge to the bus voltage

and should not be too big of capacitance and mid-leg resistor value and the amount of energy pulses per second that goes through the resistor should consider respectively.

4.2 Hardware consideration for MVDC SSPD application

There are some parameters that should be considered when designing a MVDC protection device like surge current tolerance, device wafer size and operating temperature. Hardware assessment and reliability that is attached to this selection plays a significant role in the system survivability. Some of the considerations are:

- High current protective devices- this comes from the fact that to get to the higher current and voltage, making blocks of series and parallel modules is inevitable. Stacking of devices seems to be common in industry, but not paralleling. For each parallel connection, the parasitic interconnecting inductances drive a need for additional voltage clamping snubbers—which drive up the size and drive down the reliability of these devices. [7]
- Technical readiness of module technology- packaging the module to achieve safe operation within the voltage and current requirements in one big challenge also the number of modules to use in stack both in parallel and in series to handle the system current and voltage within the MVDC range is another important characteristic to consider.

- Heat sink ground isolation- switching power electronics inherently produce high *dv/dt* voltage pulses with respect to the heat sink. These pulses act upon the parasitic capacitance that is naturally existed between device junctions and cases which are mounted to the heat sink. If the heat sink is grounded, then these pulses give a rise to capacitance induced current to ground at the switching frequency. These common mode currents are the cause of EMI and can affect system operation.
- Protective system design- coordination between various parts of protective devices in the system helps to achieve and adequate protective measures throughout the system. like no load over current protection or pole-to-pole and pole-to-ground fault discrimination helps the well integrity and efficient operation of the SSPD.

There are various available options based on different chip technology like IGBT, GTO and SGTO. Each has its own benefits and trade-offs that reviewed as below.

To make it easier to make comparison between different chip technology, SiC considered as the base for comparison.

Since SiC devices has smaller voltage drop that Si, it serves well in power conversion applications but due to smaller chip surface it can't handle that much of surge current than those of Si. This is not very beneficial for SSPD application since handle large amount of current in brief period, is more important. This is directly related to reliability of SSPD which plays a key role in survivability of system in the matter of fault.

Bipolar Junction Transistor (BJT) can achieve bigger size hence higher current compare to SiC IGBT, SiC ETO, SiC GTO but also has a higher switching loss which is not a case in SSPD application. [5], [6]

4.3 Design and implementation

4.3.1 MATLAB Design

The figure above shows the prototype SSPD on the positive bus. As it is mentioned in the context, the controller observes voltage and current passing through the bus by sensors. All these comprehensive data are valuable tools for controller to even predict what will happen if it encounters with an unusual situation (like over current or under voltage etc.) Based on pre-defined algorithm.

This SSPD is designed not only protect the system from pole-to-pole or pole- ground fault, but against any over current situation that is not a normal condition. To simplify the design and simulation, unidirectional schematic used to verify the results.

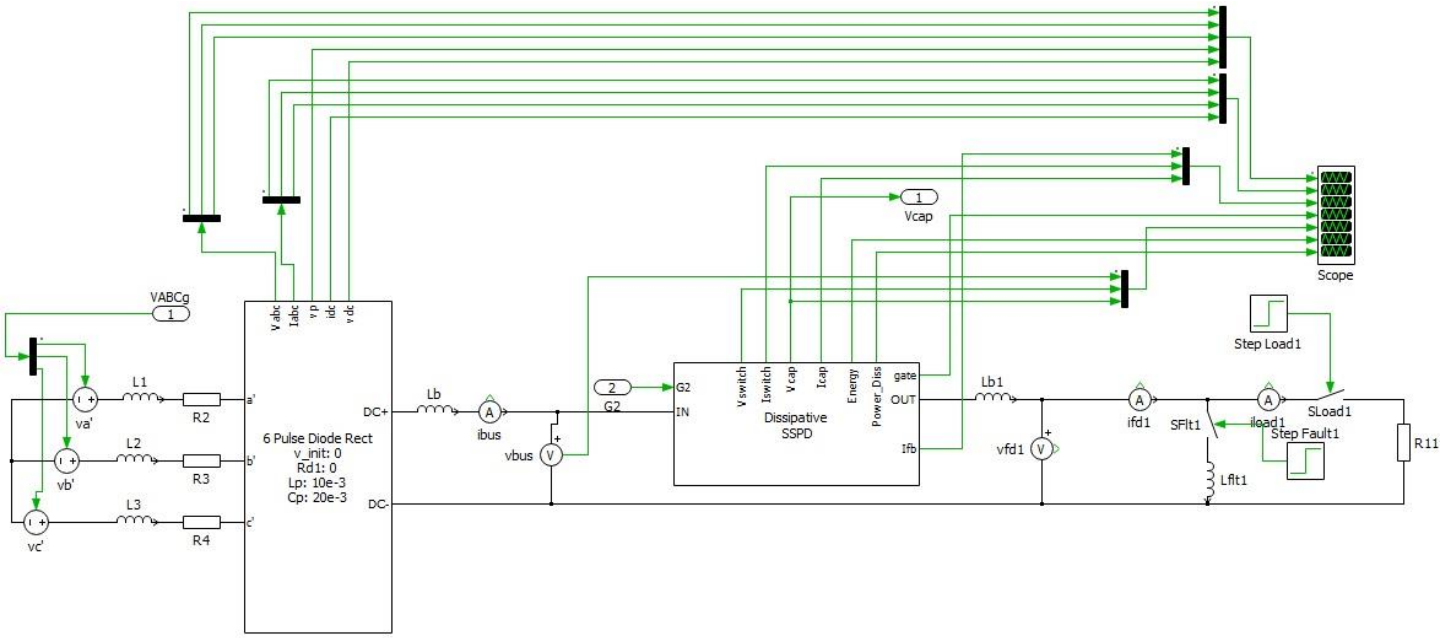


Figure 4.5 SSPD schematic

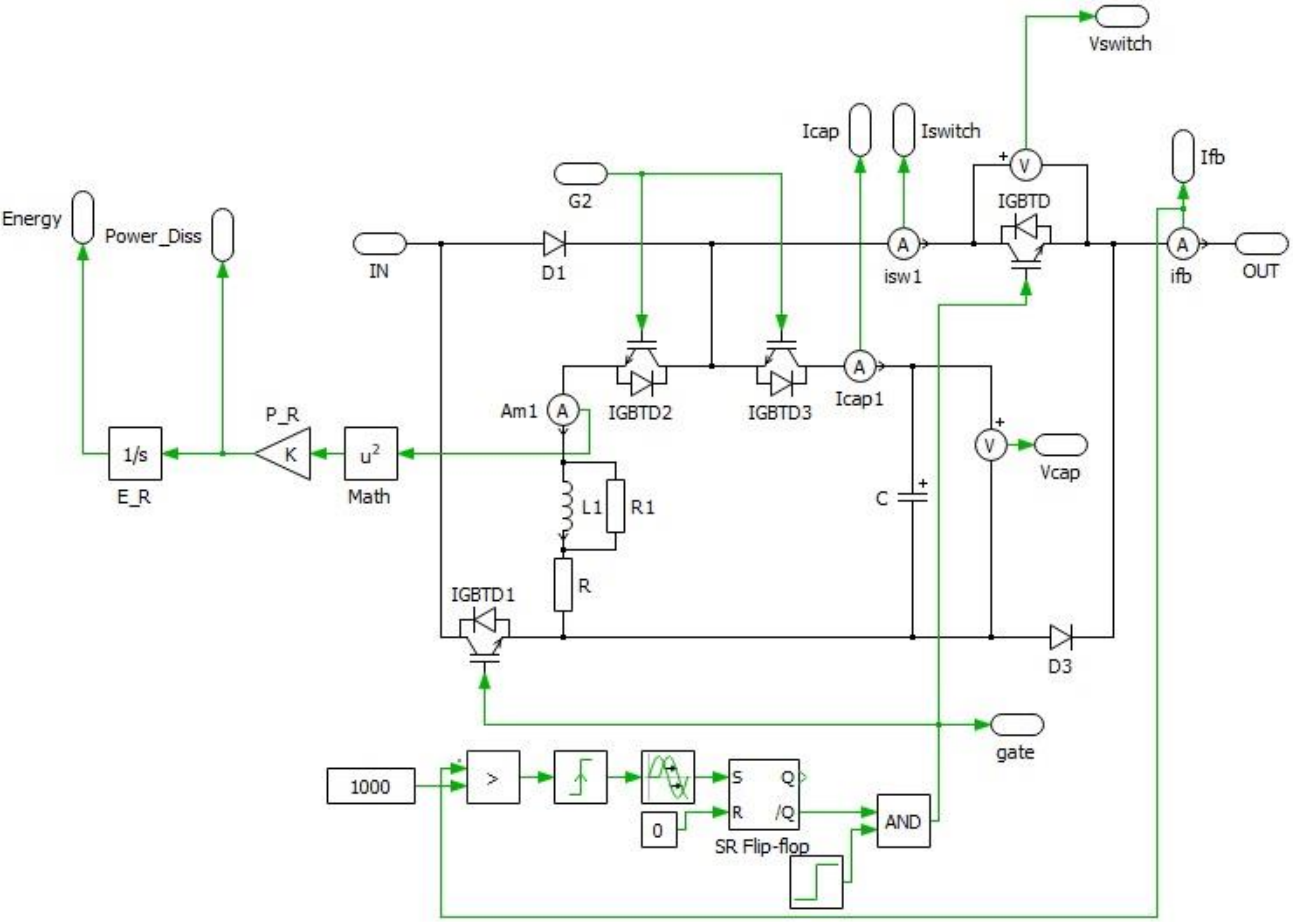


Figure 4.6 Simplified Scheme of the circuit breaker.

As it is shown below, there are two passes for current through D1 and T2c from left to right and also from D3 and T4 from right to left. This indicates that, this design capable of a bi-directional protection from source to load and also from load to source.

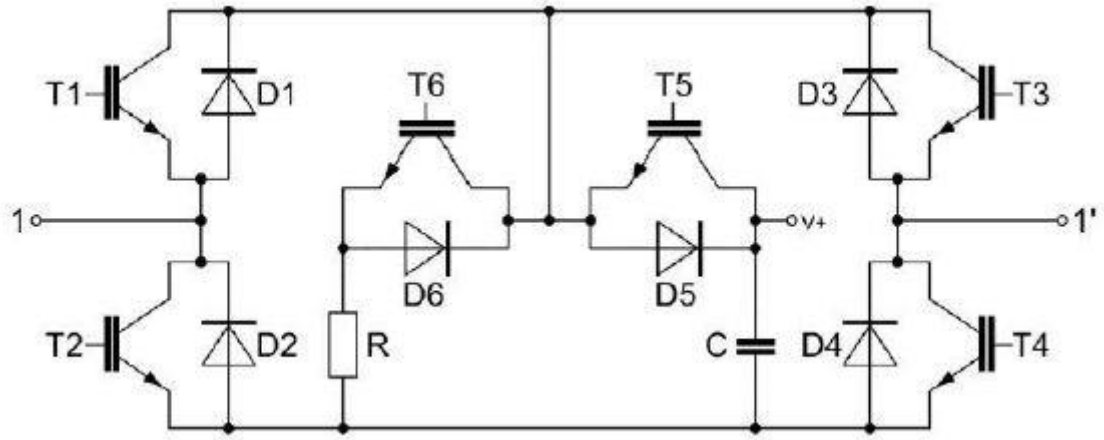


Figure 4.7 Scheme of SSPD

First State (Normal condition): current flows from both legs and charge capacitor in the mid-leg.

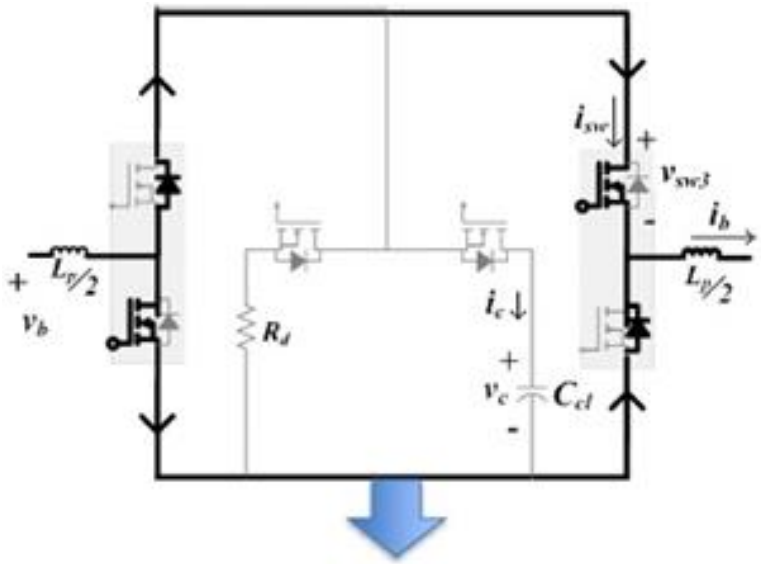


Figure 4.8 Normal operation

Second State (Fault): in this scenario, controller turn off T2 and the energy redirect to mid-leg and cap to avoid damages to the switch and circuit components. At the same time sensors measuring cap voltage and providing data for controller. When the caps reach the certain voltage controller signal the gate drive to the next stage.

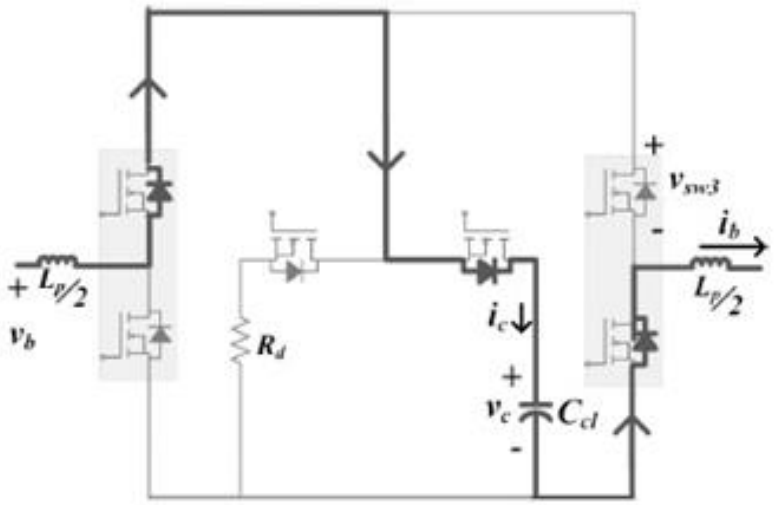


Figure 4.9 Fault condition

Third State(Dissipation): in this stage caps voltage reaches the desire level and controller turns T5 and T6 on in the middle leg and reroute the energy to high-performance reisitor R_d to dissipate (burn) it. At this time, the excessive amount of energy due to short circuit is safely managed.

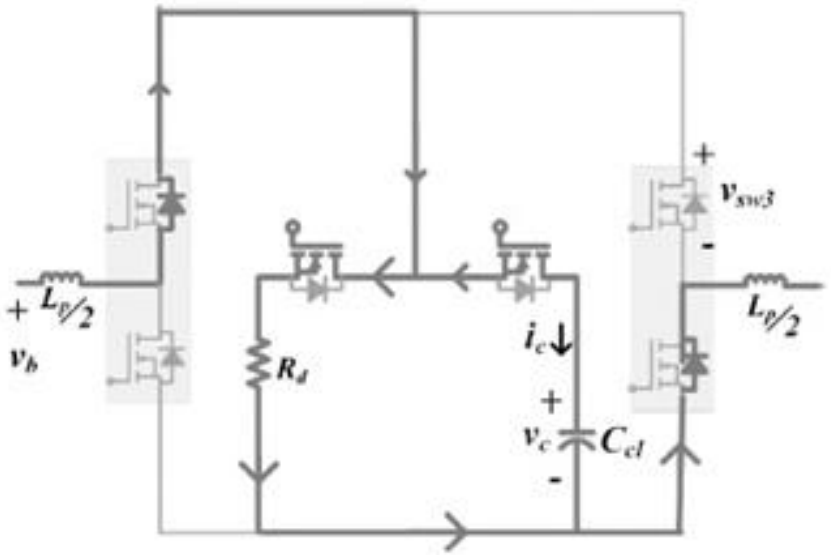


Figure 4.10 Dissipating stage

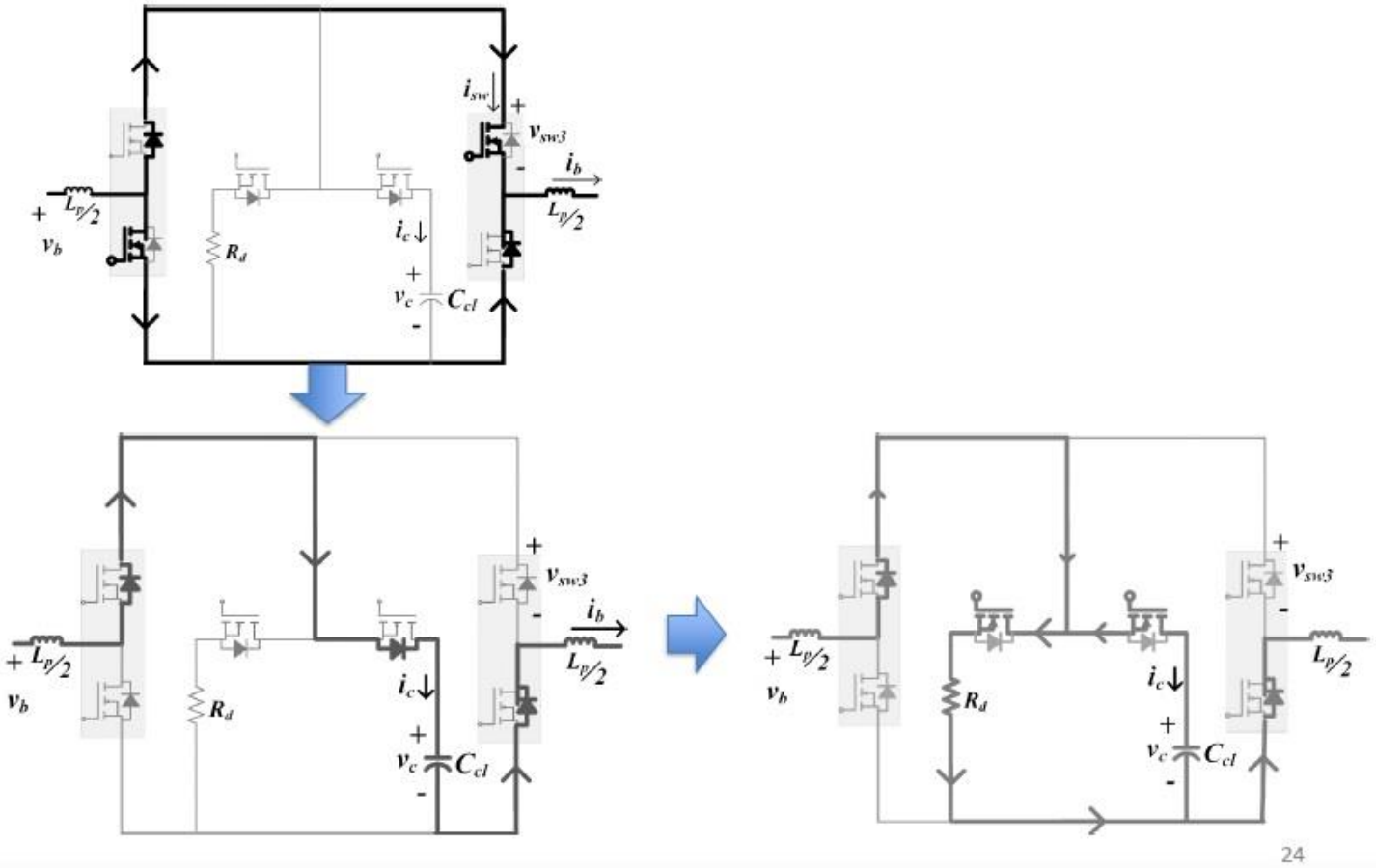


Figure 4.11 stages of operation

4.4 Hardware configuration

There are 6 main components to this project:

Heat sink

FPGA controller

IGBT switches

Capacitors

High performance resistor

Copper bus plate

4.4.1 Heat sink:

It provides a foundation for the rest of components. IGBT switches mount on the top of heat sink but most importantly, it provides a surface for heat to scape and dissipate into the surrounding.

Before the thermal modeling, in order to get a clear understanding of the objective and result of the PLECS model, the concept of a thermal circuit is necessary to be explained. In an electrical circuit, applying Ohm's low, **Error! Reference source not found.**can be written as follow:

$$R_{th} = \frac{\Delta T}{PD} \qquad \textit{Equation 4.1}$$

Where R_{th} is the thermal resistance, ΔT is the ambient temperature, P_D is the power dissipation. shows the thermal circuit and parameter relationships for one device with heat sink.

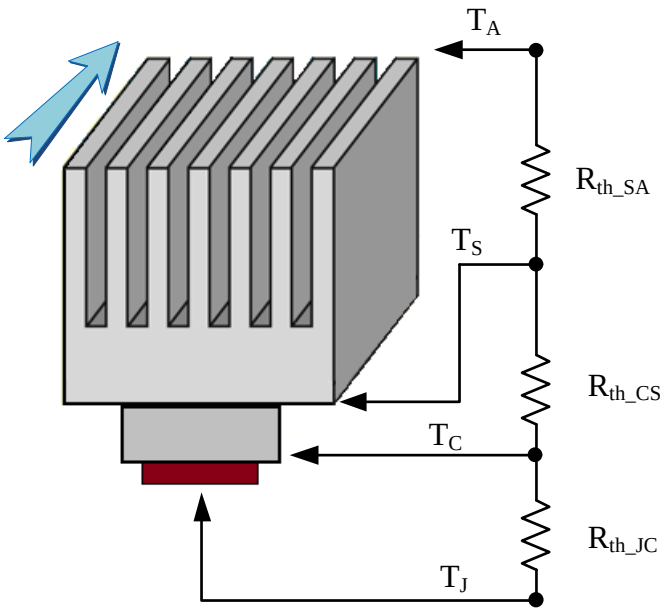


Figure 4.12 Thermal circuit for device with a heat sink

Where T_A is the ambient temperature, R_{th_SA} is the heat sink to ambient thermal resistance, T_S is the heat sink temperature, R_{th_C} is the case to heat sink thermal resistance, T_C is the case temperature, R_{th_JC} is the junction to case thermal resistance, T_J is the junction temperature.

The relationship of power dissipation, temperature, and thermal resistance is shown below:

$$R_{th\_JA} = \frac{T_J - T_A}{P_D} \qquad \text{Equation 4.2}$$

Where R_{th_JA} is the thermal resistance from junction to ambient. P_D is the power dissipation of the device. In this case Junction to Ambient resistance defined as below:

$$R_{th\_JA} = R_{th\_JC} + R_{th\_CS} + R_{th\_SA} \qquad \text{Equation 4.3}$$

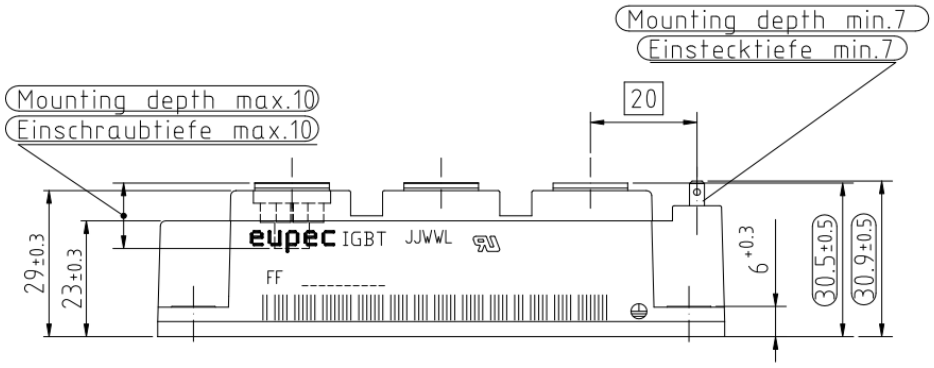


Figure 4.13 Packaging outline

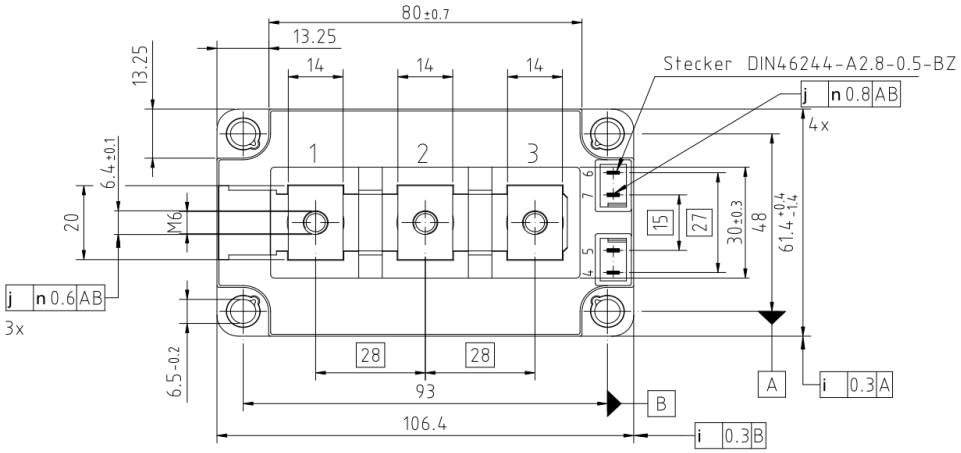


Figure 4.14 packaging outline

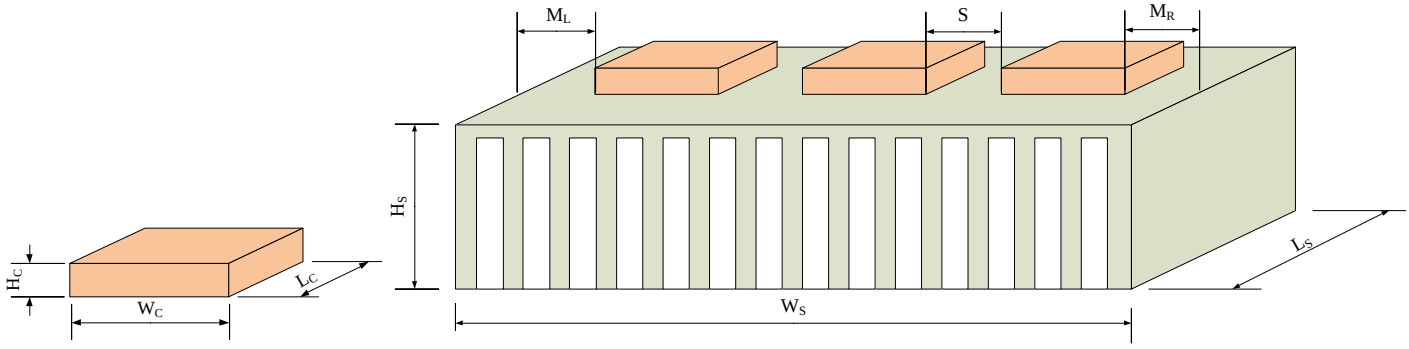


Figure 4.15 IGBT with heat sink

In order to get the volume of heat sink, the length of fin L_S need to be determined. It is assumed that the fin is perpendicular to the air flow direction, so the length of the fin is in the same direction of air velocity. Both the fin spacing, and air flow condition are matter for the selection of fin length. In general, the more surface area a heat sink has, the better it works, so a smaller fin spacing should be considered in a design. However, for a certain width of heat sink, smaller fin spacing means more fins, and that can lead to adverse effects on pressure drops and flow bypass, and the average heat transfer coefficient goes down. Also, for a higher fin density, the manufacturing process is more difficult, which will lead to higher cost.

4.4.2 FPGA Controller (DE 10-standard Development Kit)

The DE10-Standard Development Kit presents a robust hardware design platform built around the Intel System-on-Chip (SoC) FPGA, which combines the latest dual-core Cortex-A9 embedded cores with industry-leading programmable logic for ultimate design flexibility. Intel's SoC integrates an ARM-based hard processor system (HPS) consisting of processor, peripherals and memory interfaces tied seamlessly with the FPGA fabric using a high-bandwidth interconnect backbone.

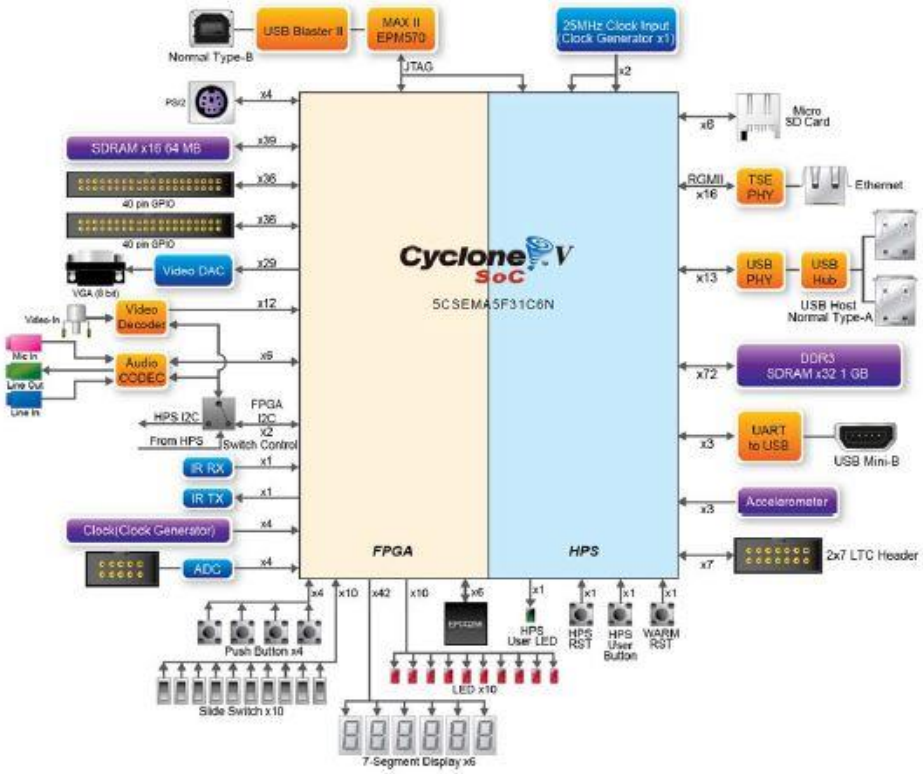


Figure 4.16 Block diagram of DE10-Standard

Based on SSCB application, there are 3 stages of operation

Normal condition

Fault condition

Energy Dissipation process

As shown below, in each stage current route defined by the gate drive signal and turning ON or OFF the designated switches respectively.

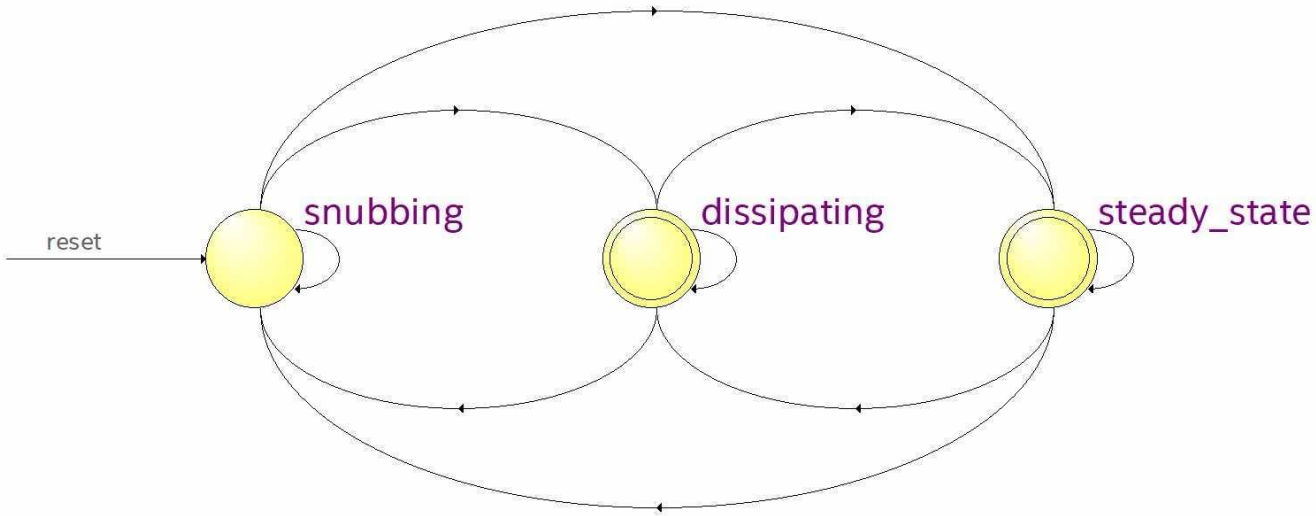


Figure 4.17 Controller State Machine

First state

In normal operation, two switches signal to conduct by the controller. Other switches in mid-leg stays off.

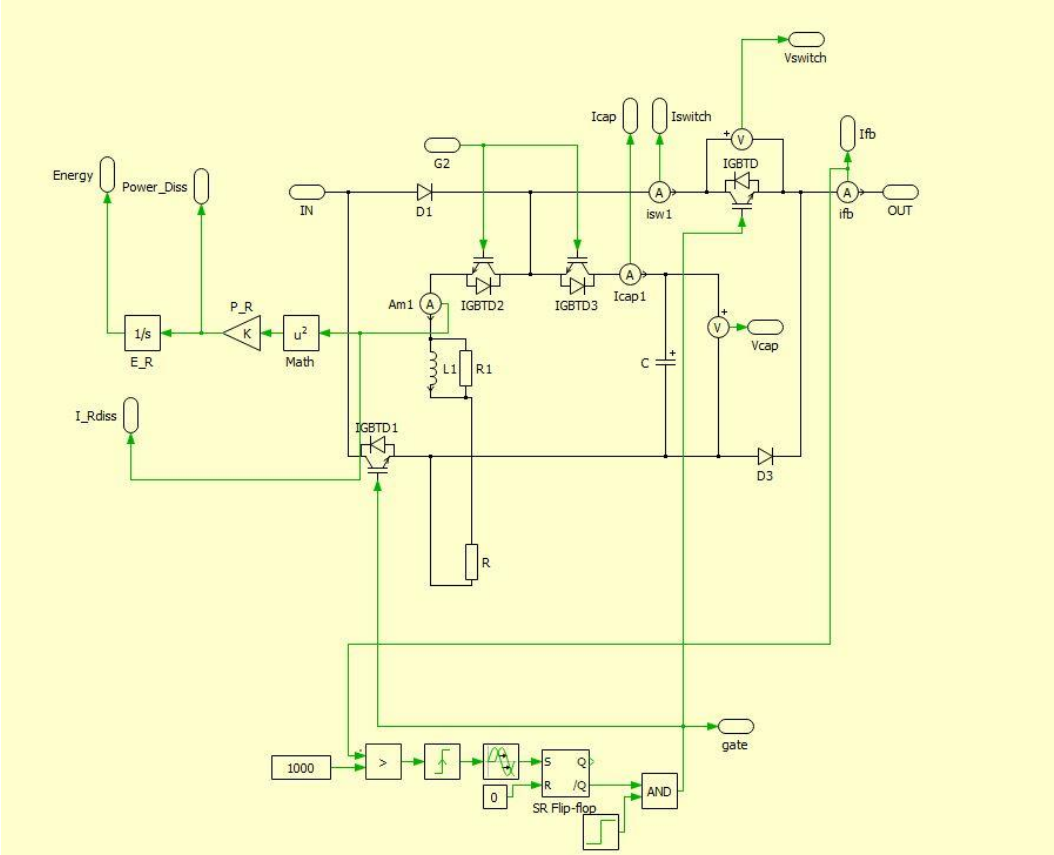


Figure 4.18 schematic of conduction state (PLECS)

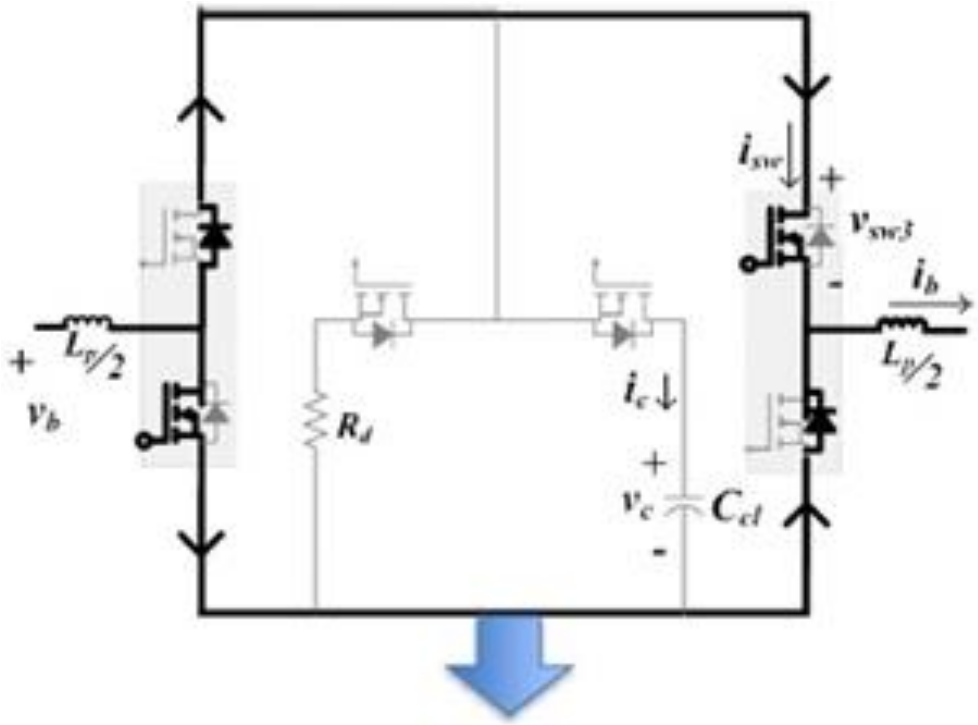


Figure 4.19 schematic of conduction state (MATLAB)

Fault: switches OFF to prevent over current over switches and then dissipation stage to burn-off the excessive energy caused by the fault (mostly short circuit)

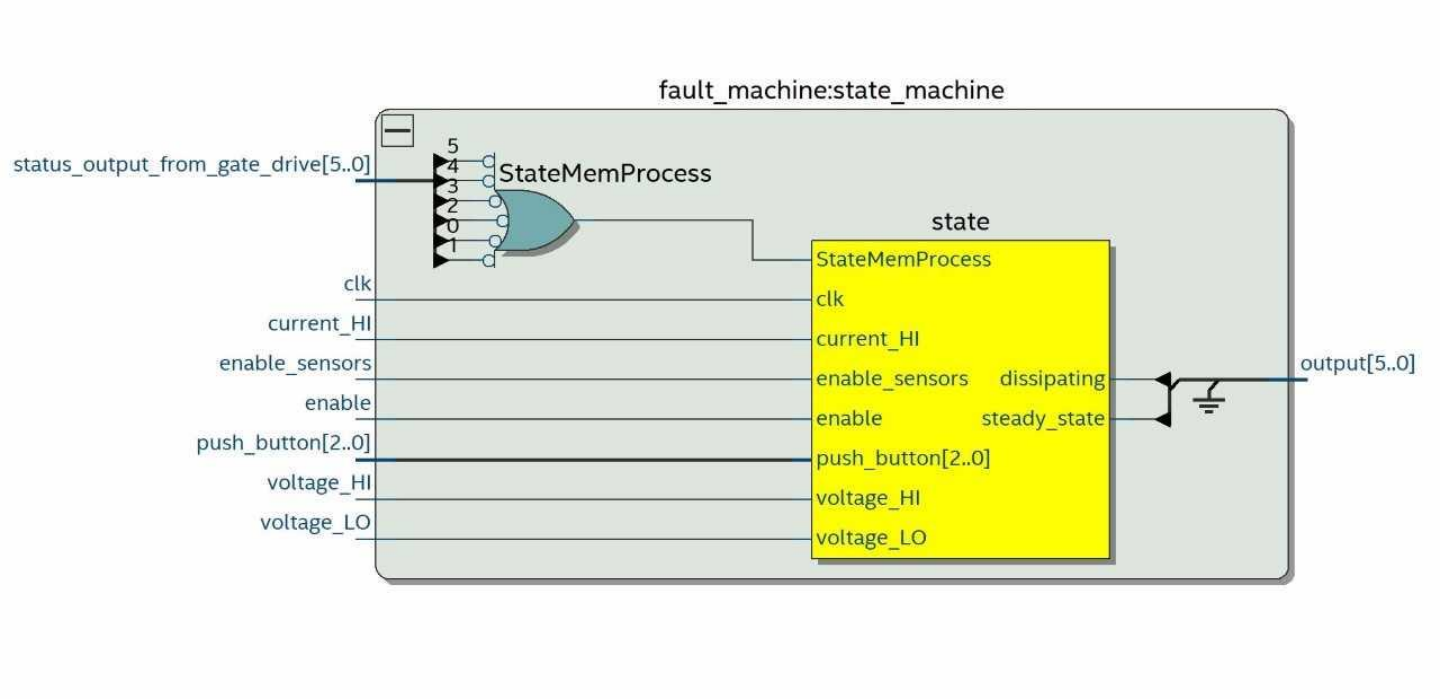


Figure 4 Fault and dissipation State Machine

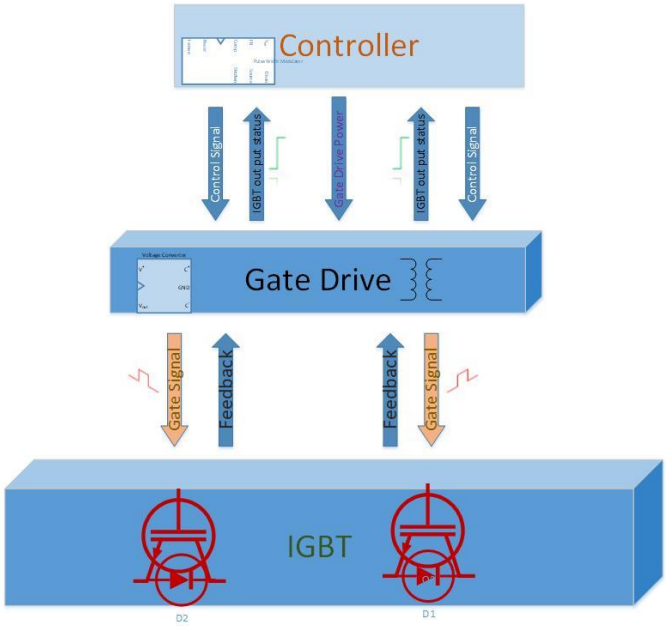


Figure 4.21 Controller, gate drive and IGBTs interaction

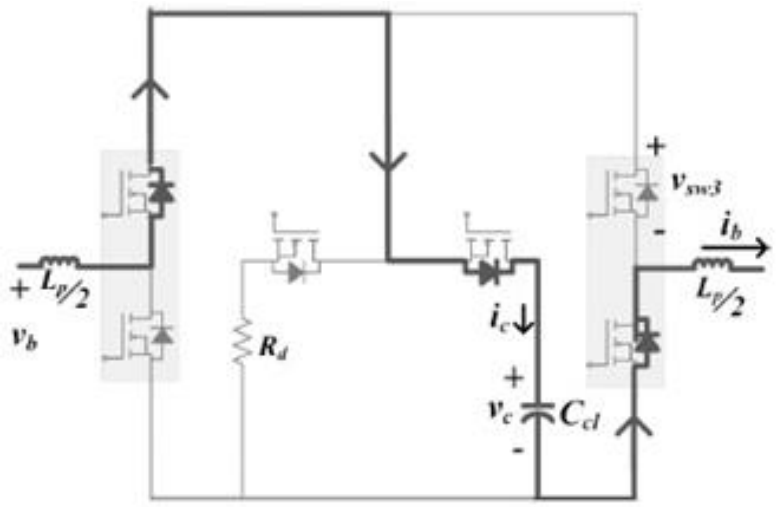


Figure 4.22 Switches in fault situation

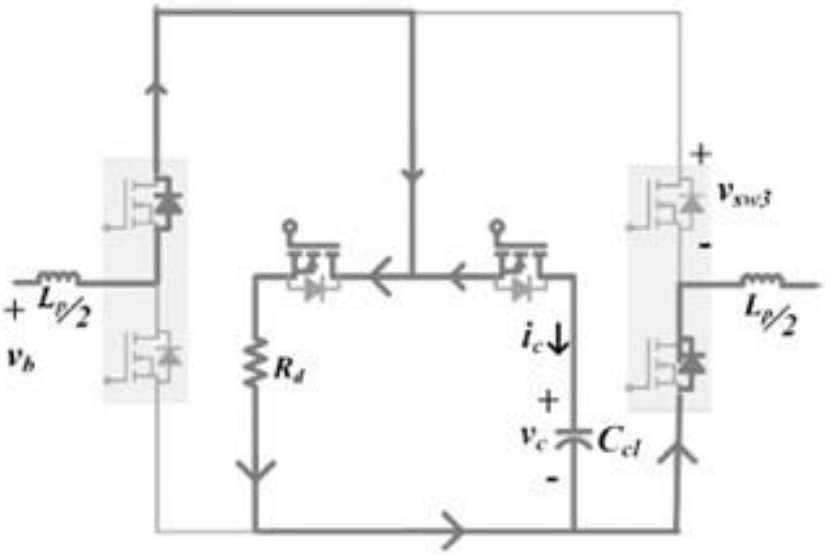


Figure 4.23 switches in dissipation stage

4.4.3 IGBT Switch

PrimePACK™ 3 IGBT module and NTC is capable of 3-level application for high power converters, motor drives and wind turbines.

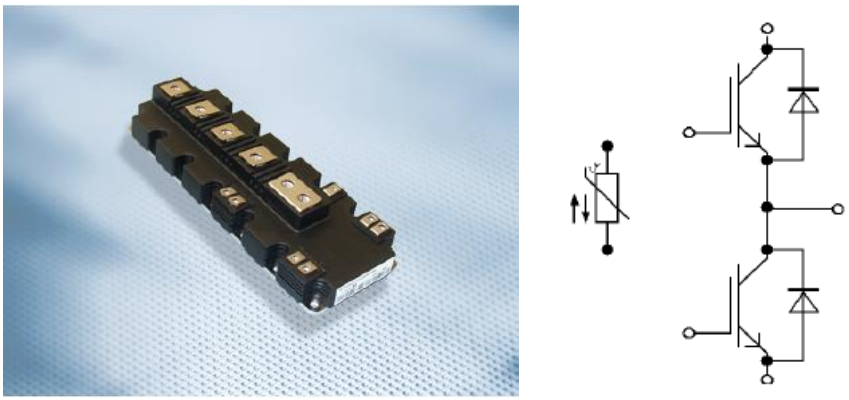


Figure 4.24 PrimePACK™ 3 IGBT-module (FF1000R17IE4) [10]

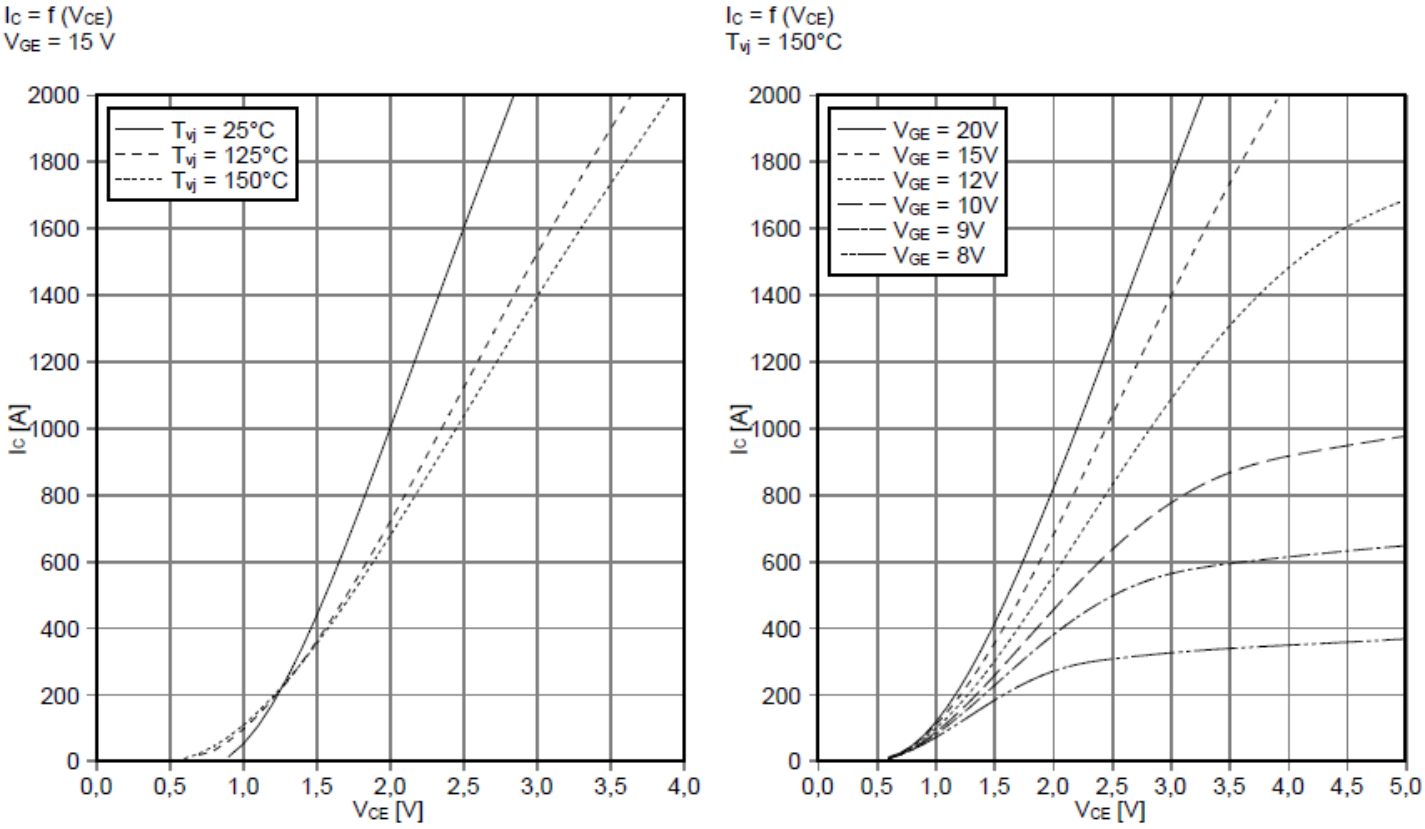


Figure 4.25 typical characterization of IGBT switch [10]

Selection of switches for different applications requires extensive understanding of the module characteristics.

Collector-emitter voltage @ T_{vj} = 25°C, V_{CES}=1700 V	Gate charge $Q_{G\ Gate\ charge}$=10 µC	Internal gate resistor @ Tvj = 25°C R_{Gint} =1.5 W
Collector-emitter saturation voltage I_C = 1000 A, V_{GE} = 15 V, T_{vj} = 25°C, V_{CEsat}=2-2.45 V	I_{CES} =5.0 mA V_{CE} = 1700 V, V_{GE} = 0 V, T_{vj} = 25°C	Turn-off delay time, inductive load I_C = 1000 A, V_{CE} = 900 V @ T_{vj} = 25°C, $T_{d\ off}$=1 µs
Continuous DC collector current T_C = 100°C, T_{vj} max = 175°C, I_{Cnom} =1000 A	Continuous DC collector current T_C = 25°C, T_{vj} max = 175°C, I_{Cnom} =1390 A	Rise time, inductive load I_C = 1000 A, V_{CE} = 900 V, V_{GE} = ±15 V, @ Tvj = 25°C, T_r=0.1 µs
Total power dissipation @ T_C = 25°C, T_{vj} max = 175°C, P_{tot}=6.25 KW	Collector-emitter cut-off current V_{CE} = 1700 V, V_{GE} = 0 V, T_{vj} = 25°C I_{CES} =5 mA	Fall time, inductive load I_C = 1000 A, V_{CE} = 900 V, V_{GE} = ±15 V, @ Tvj = 25°C, Tf=0.29 µs

Table 5 PrimePACK™ 3 IGBT-module characteristics

4.4.4 IGBT gate drive

The 2SP0320T is a dual-channel driver with an electrical interface. The driver is based on CONCEPT's SCALE™-2 chipset, a highly integrated technology for the reliable driving and safe operation of IGBTs. Perfectly matched driver versions are available for all corresponding IGBT modules from Danfoss, Fuji and Infineon. The plug-and-play capability of the driver allows immediate operation after mounting. The user needs invest no effort in designing or adjusting it to a specific application.

This is a set of application-specific integrated circuits (ASICs) that cover the main range of functions needed to design intelligent gate drivers. The SCALE-2 driver chipset is a further development of the proven SCALE technology. The driver contains all necessary components for optimal and safe driving of the relevant IGBT module: smallest gate resistors in order to minimize switching losses, gate clamping, active-clamping diodes (overvoltage protection at

turn-off), VCE monitoring (short-circuit protection) as well as the input electrical connector X1. Moreover, it includes components for setting the turn-off trip level, the response time and the dead time between both channels in half-bridge mode. Its plug-and-play capability means that it is ready to operate immediately after mounting. The user needs invest no effort in designing or adjusting the driver to a specific application.

Figure 4.26 Gate Drive mounted on top of IGBT switch

The basic topology of 2SP0320T driver is shown below:

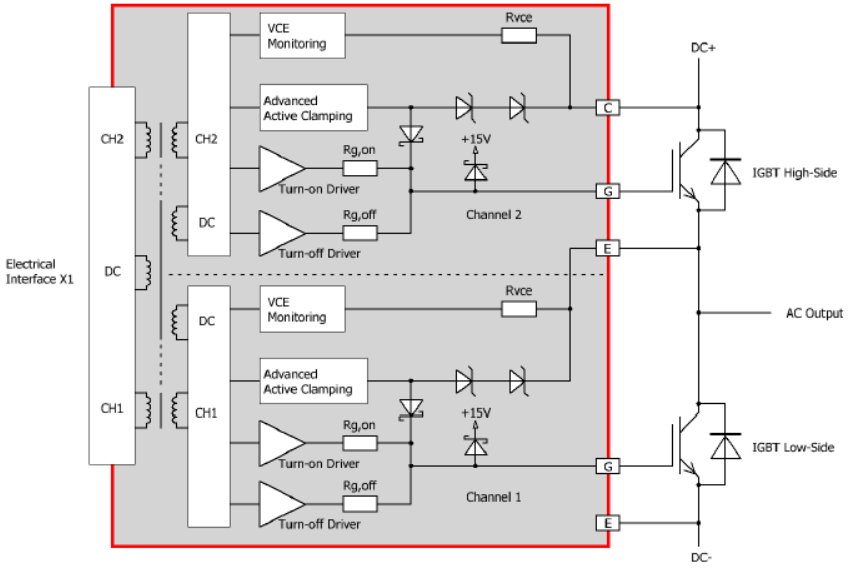


Figure 4.27 Basic schematic of the 2SP0320T driver

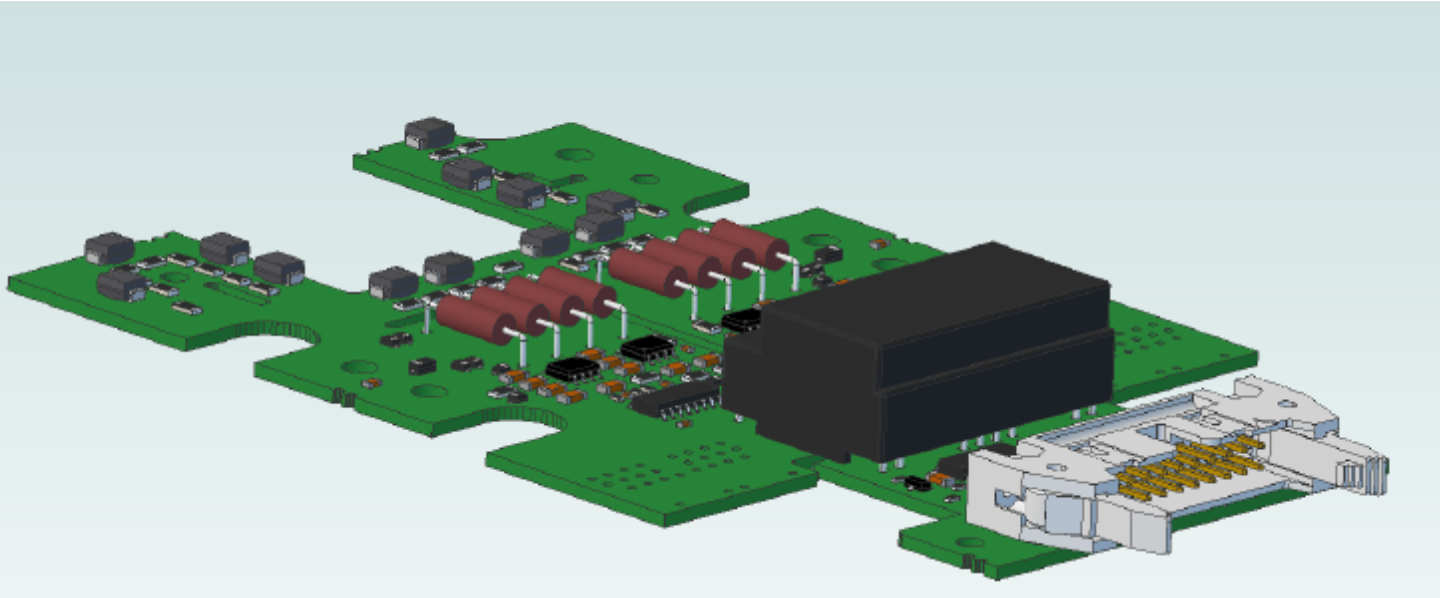


Figure 4.28 3D drawing of 2SP0320

The driver contains all necessary components for safe and smooth operation of IGBT module. Optimal operation acquired by selecting the relevant connector and twisted cable to connect drive terminal to the controller. Here is some information about electrical connection between the drive and controller and how to designate pins from X1 connector to the controller. Electrical connector on the driver: 71922-120LF from FCI, recom. cable connector: 71600-020LF from FCI recommended twisted pair flat cable: 1700/20 or 2100/20 from 3M™.[11]

Pin	Designation	Function	Pin	Designation	Function
1	VDC	15V for DC/DC converter	2	GND	Ground
3	VDC	15V for DC/DC converter	4	GND	Ground
5	VCC	15V for primary side electronics	6	GND	Ground
7	VCC	15V for primary side	8	GND	Ground

		electronics			
9	SO2	Status output channel 2	10	GND	Ground
11	INB	Signal input B	12	GND	Ground
13	SO1	Status output channel 1	14	GND	Ground
15	INA	Signal input A	16	GND	Ground
17	MOD	Mode selection (direct/half-bridge)	18	GND	Ground
19	TB	Blocking time	20	GND	Ground

Table 6 Pin designation od connector X1[11]

Figure 4.29 Gate drive, IGBT and X1 connector [11]

4.4.5 Capacitor

The UL Film capacitor series represents the best choice for high power DC applications because of different electrical and physical characteristics in different conditions.

Figure 4.30 UL series [13]

Low ESR, low inductance (as low as 25nH), high current carrying and withstand hostile environment make this capacitor an excellent candidate for PE applications.

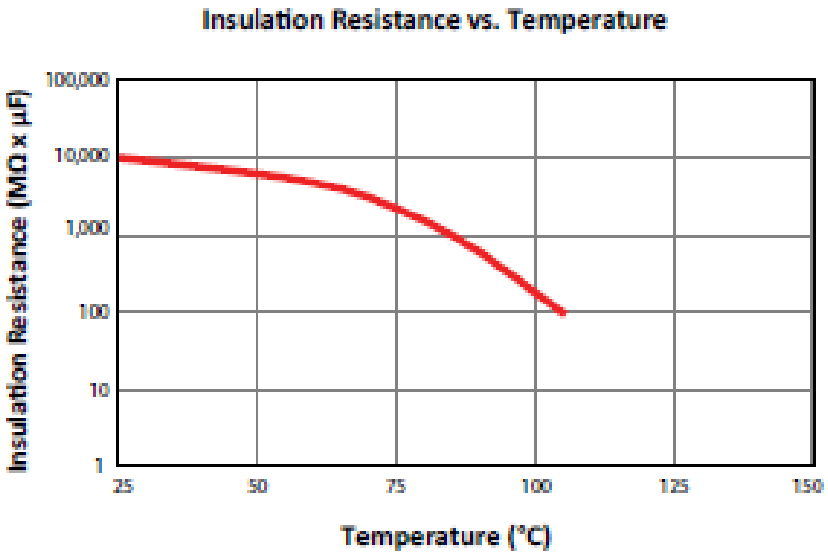


Figure 4.31 Dielectric strength [13]

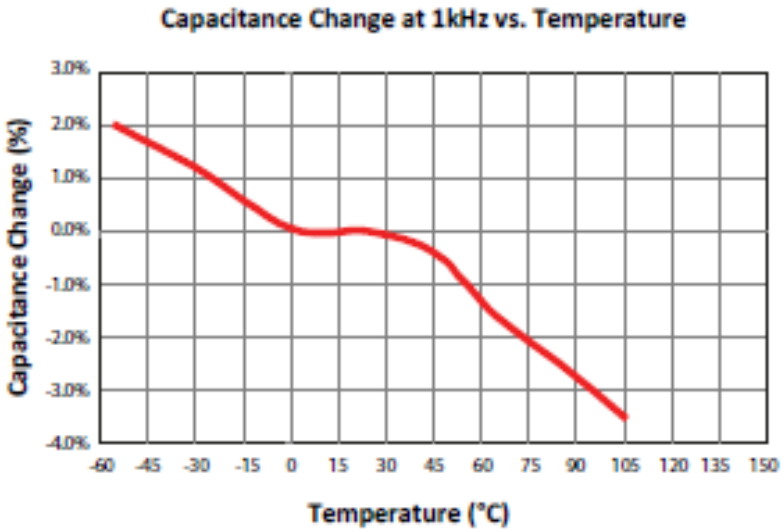


Figure 4.32 Capacitance changes Vs. Frequency [13]

4.4.6 High performance resistor

With the capacity of sustaining under high energy pulses (12k Joules) and maximum impulse volts of 20.4 KV, this round disk can withstand high energy discharges.

Figure 4.33 HVR high surge energy resistors [14]

Power dissipation

Continuous power dissipation for High Energy Disk resistors is a function of mounting method used. In free air, .25 watt per cm² of exposed surface area is a conservative rule of thumb. Thus,

a 50mm disk with both faces and the periphery exposed could easily dissipate 20 watts. Higher power dissipation is achieved by conduction cooling through the mounting surface, applying an air or water-cooled heat sink to either or both faces. [14]

4.4.7 Copper bus plate

This copper plate designed to withstand 2500 VDC and over 100A current. By minimizing wire connections, parasitic inductive in system reduces. In this case most of the inductive effects related to the internal structure of the generator.

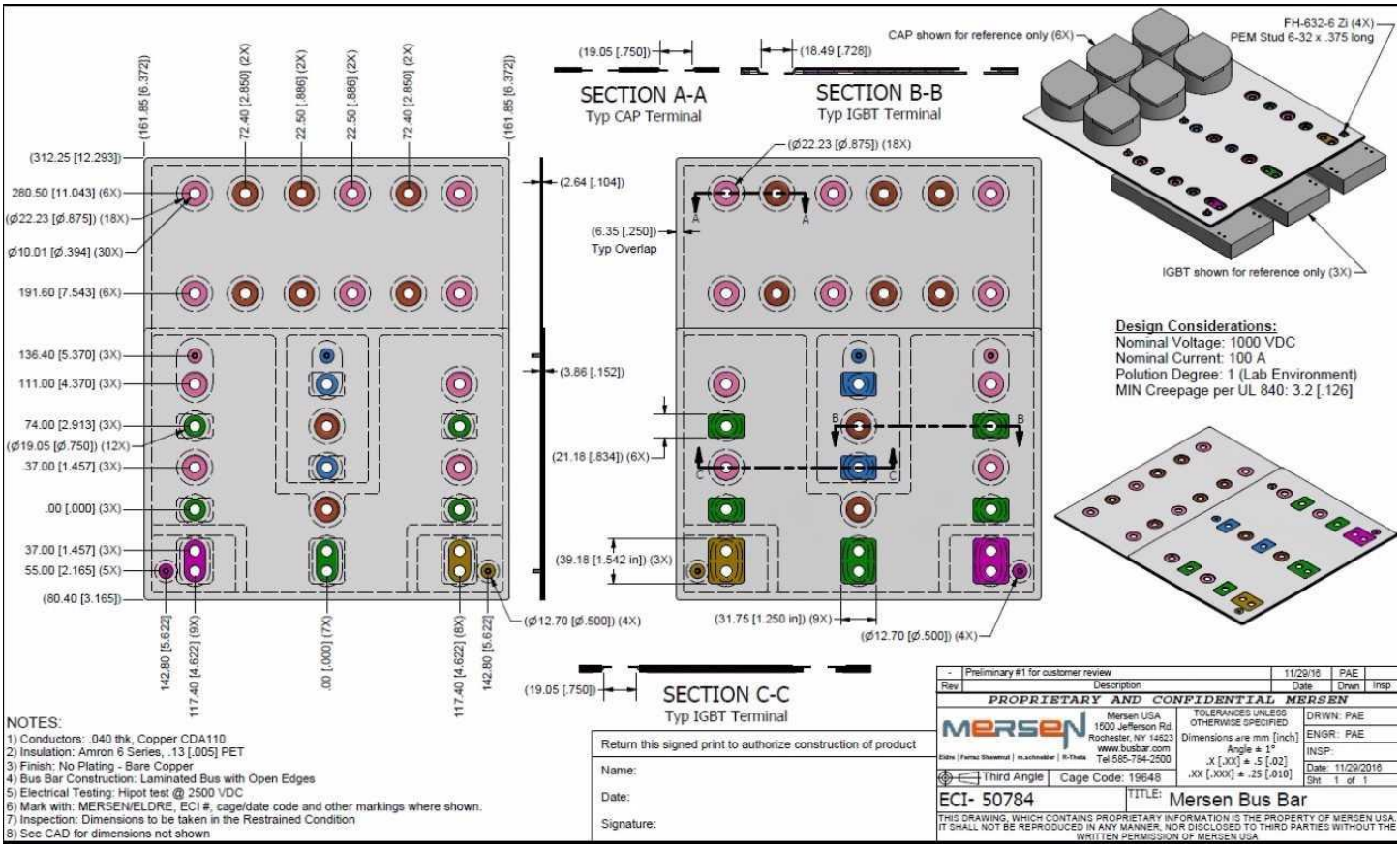


Figure 4.34 MERSEN copper bus plate

Here is the lab set up for the test. The future work on this project is to integrate a current and voltage sensor to collect data from the bus.

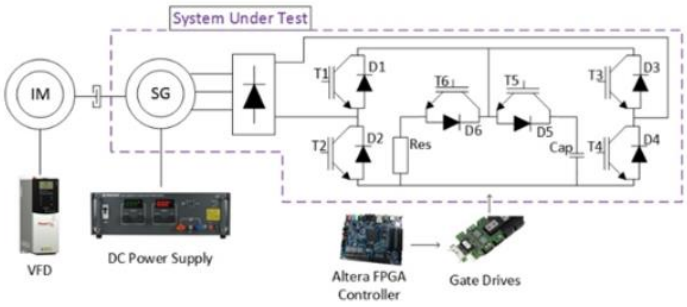


Figure 3. Experimental Setup to validate H-bridge hard-

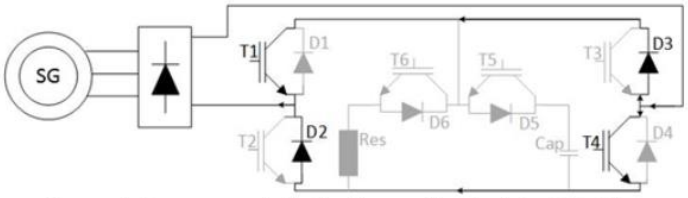


Figure 4. Current path during line to line fault in H-Bridge

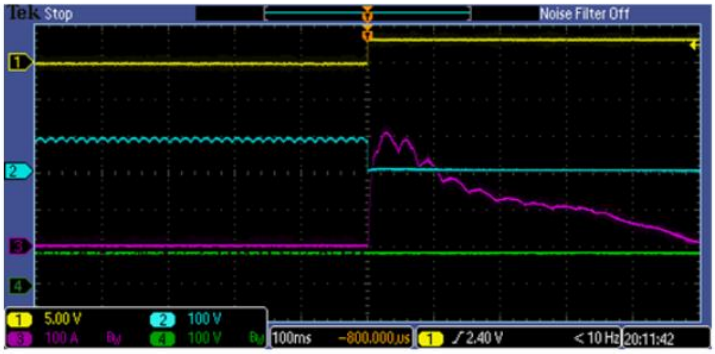


Figure 5. Ch1: Gate Signal. Ch2: DC bus voltage. Ch3: DC bus current. Ch4: Capacitor voltage.

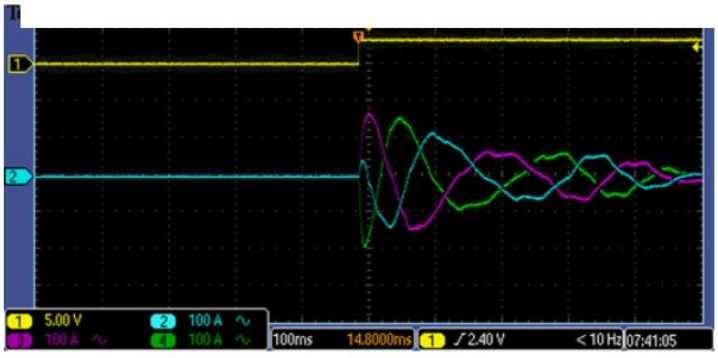
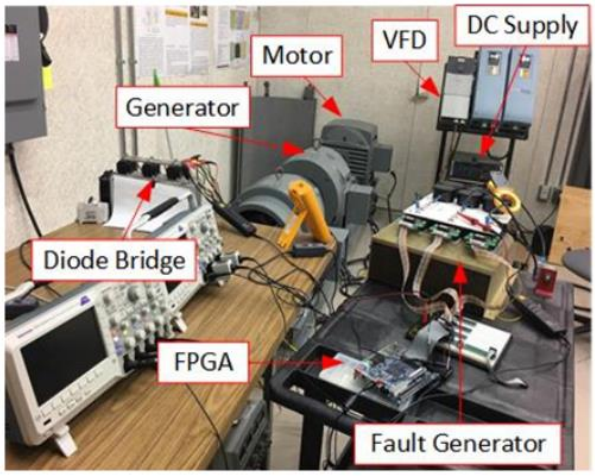


Figure 6. Measured results of AC fault currents. Ch1: Gate signal. Ch2, 3, and 4: AC bus currents. Measured results of DC fault current



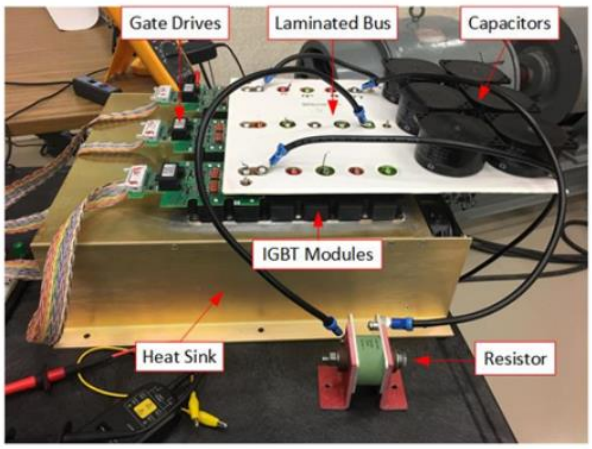


Figure 7. Experimental Setup in Figure 2 (Top), IGBT H-bridge module (Middle), Heat Sink Fans (Bottom).

Figure 4.35 Lab set up and short circuit test results

The generator sub-transient and transient reactance produce different fault current wave forms than is mentioned in IEC Standard 61660-1[16] and were validated experimentally in [15]. This difference shows the need of automated testbed to study these fault characteristics. This hardware presents static Line-to-Line fault test. As it is shown below, integrating NI Compact RIO into the system would help to provide automated testbed.

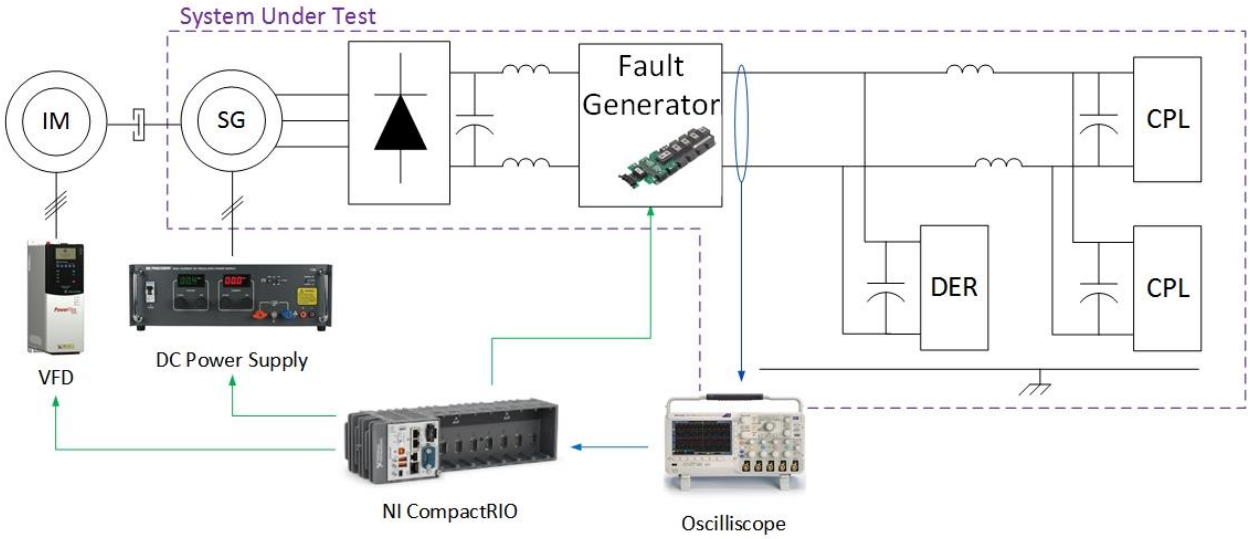


Figure 4.36 Future automated testbed

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