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Protecting A Low Voltage Direct Current System Using Solid-State Switching Devices for DC Grid Applications

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Abstract: Low voltage DC (LVDC) distribution system has less distributional losses than AC grid, integrating renewable sources, greatly increasing the mix of clean energy sources in the standard grid in the next decade and this has become a trend that is likely to continue. As an additional benefit, DC electrical power is oftentimes seen as beneficial to applications that use cleanly generated, renewable power. Considering LVDC power system design, and focusing on fault protection and the systems DC circuit breaker, are system priorities. Only solid-state circuit breakers (SSCB) should be considered to obtain advanced system topography. A new type of solid state circuit breaker is being developed as a new power device for LVDC power networks to replace the EMCB. The only suitable candidate for this task is the insulated gate bipolar transistor (IGBT). Development of DC grid protection allows for the development and improvement of new power electronic devices, focusing in on the application for medium to low voltage DC grids, a rapidly acting switching function as well as fault current limiting features. To avoid nuisance tripping, fault current limiting function can be satisfactorily accomplished by extending the elapsed time using the same control circuit. This paper presents a novel LVDC circuit breaker model, which uses a coupled inductors circuit breaker, a designed model of IGBT showed and discussed and developed an LVDC system for grid applications.

Keywords: DC protection, Insulated-gate bipolar transistors (IGBTs), LVDC power system, solid-state circuit breakers (SSCB).

1. INTRODUCTION

LVDC electrical energy using renewable environmentally friendly power is frequently seen in many applications as helpfully modern. Considering the design of DC power systems, it is important to focus on fault protection and maintain the power system's DCCB. Only solid-state circuit breakers should be considered for installation and applied to these types of systems because these are the only types breakers that respond quick enough to faults to prevent damages even though they tend to have a greater rate of power loss than other breaker types. SSCBs are pure semiconductor devices that monitor all the behaviors of the IGBT which are tremendously important to switching transitions. Solid state LVDCCBs make use of a completely manageable power semiconductor device from the primary branch to interrupt electrical current and doesn't require a mechanical switch. They interrupt DC current very effectively

The idea being introduced in this system is a new type of DC solid state circuit breaker with transformer coupling that uses coupled inductors to detect and isolate faults. These types of circuit breakers gain advantages over other types of circuit breakers because they

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don't have as many parts and has an adjustable current threshold that can be set to operate when the level of current rises past the set threshold causing the circuit breaker to trip [1-6]. Normally, the circuit breaker is in the system between the source and the load. SSCBs are used in high voltage systems because they have a swift switching speed and interrupt high voltage DC current very efficiently.

During fault interruption, the rapidly dropping current will expose the SSCB to serious strain due to overvoltage. If this is left uncorrected, this overvoltage can easily cause the SSCB to become unresponsive and might possibly damage the sensitive devices inside the SSCB [7], [8]. To address this issue, it is necessary to install a snubber circuit to protect the system by suppressing overvoltage. Having an installed snubber circuit becomes essential to the safe turn off of the system. There are some requirements that should be able to be met by the snubber circuit. It should be highly reliable for medium capacity, low voltage applications. Overvoltage should cause a minimal level of stress to the SSCB at turn off.

The presence of a snubber circuit that has been designed and specialized for precise application in SSCBs is of extreme importance. Generally, methods of snubber design anticipate that snubbers be must be suited for converter switches and thus, they cannot be applied directly to the SSCB snubber. There are many reasons for this. Reduction of snubber loss as well as rapid suppression features do not get lots of attention in SSCB snubber design because of inconsecutiveness as well as infrequency of SSCB switching. Suppression of overvoltage as well as ability to withstand fault current are the features which receive the most attention in SSCB snubber design due to the magnitude of fault current that is met and, as a consequence, SSCBs become exposed to high overvoltage [7-10]. This paper is organized as follows: section two covers related work, section three present the background of the LVDC system and protection using SSCB for LVDC grid applications. In section four, analytical analysis of proposed dc protection circuit is presented. In section five, examination of IGBTs for implementation in LVDC SSCB is covered. Section six presents modeling the LVDC system under study and section seven conclusion.

2. RELATED WORK

Certain advancements in the field of power electronics have been ongoing and LVDC systems are looking more advantageous than they ever and have also become increasingly dependable since the application of grid distribution, advanced circuit breaker technology, power converters and other LVDC protective devices. New microgrids will be perceived in the DC power format and many power systems or, power conversion components are readily available but, as it applies to DC circuit breakers, many different designs are still in the experimental stages.

Circuit breakers have certain functions and duties which must be performed. A circuit breaker must be capable of performing three basic duties. It must be capable of opening the faulted circuit and breaking the current. It must be able to be closed to a fault. lastly it must be able to carry fault current for a short period of time as part of a hierarchal protection coordination scheme. In addition, it must be completely controllable. A circuit breaker must have a rapid switching speed as well as low conduction losses, no arcing, and must ensure definitive tripping of the whole breaker system. Detecting short circuits as quickly as possible is the key to minimize power dissipation in system components during fault events so that overheating and damages to a switching device, such as an IGBT, can be prevented. Various works address the need for a new and fast circuit breaker model for LVDC system applications.

One recent research proposed a bidirectional magnetically coupled T-source inverter (TSI) for LVDC systems [11]. The paper investigated the performance of a magnetically coupled T-source inverter for LVDC systems. Considering that building an ideal transformer is not possible, the coupling coefficient of the transformer, in respect to the leakage inductance, determines its performance, settling upon practical LVDC application of the TSI and its limitations were exposed in the experimental results. Analytical circuit analysis and derivation of mathematical equations were performed under ideal conditions.

Another study highlights protection of LVDC systems using a bidirectional Z-source circuit breaker [12]. Modified topologies of a Z-source LVDC with bidirectional power flow capability are introduced in the study. Conventional Z-source breaker topologies make it possible to protect unidirectional power flow. Proposed topologies in the study are a bidirectional ZSB and bi directional ZSB with a coupled inductor and can clear faults in any direction that is needed. Both topologies make use of a SCR as a switch for commutation. Coupled inductors help reduce the size of inductors, the cost and also to eliminate any need for an additional Z-source breaker capacitor.

Other recent research focuses on the design of solid-state circuit breaker-based protection for DC shipboard power systems [13]. Protection is an important aspect of DC shipboard distribution system design. It should be thought about from the very beginning design stage for reliable, low cost and efficient system operation quick action is an essential requirement for DC shipboard distribution protection. SSCB based DC protection offers very rapid protection speed and reduces the requirements on the fault withstanding limitations and fire hazards but has a high cost and losses of power because of semiconductor switching devices. DC protection methods are evaluated based upon speed and other criteria. Any optimized SSCB-based DC protection design is a compromise of the right levels of reliability, fast speed, reasonably low cost and good overall system efficiency.

Further work addresses DC microgrid protection using the coupled inductor SSCB [14]. Large scale implementation of DC microgrids depends upon the development of reliable DC protection options. The proposed DC breaker design uses an SCR to interrupt the fault current instantly. A bidirectional version of the breaker is also provided so multiple dc breakers can be installed in a notional DC microgrid. The breaker has a control switch in the design so the breaker can be opened manually without creating a large disturbance. Traditionally, a central control was proposed to supervise operations of multiple breakers in a microgrid. Two other control strategies are studied. One involves independent, local control of breakers and the other is to control breakers in pairs. The merits of all three strategies are studied. It can be concluded that within certain limitations, the paired method of control provides the desired results either a much simpler communication architecture.

The next research introduced a new DC SSCB concept using a small inductor like that used in electro-mechanical circuit breakers [15]. The new SSCB scheme uses the voltage inductor to activate short circuit protection. It is in this way that the circuit starts to open when the fault condition to prevent overload current is present [16]. Some SSCB technologies for DC are reported and can be classified into three main types, mechanicals, solid state and hybrids. Each of them have their advantages and disadvantages in respect to the others however, there are some common characteristics that are extremely important in this device, such as, time of response, electric arc suppression, high efficiency, and low cost among others. The development of new semiconductor devices with better features is entirely feasible and may improve SSCB technologies in many aspects. The new SSCB is based on two power MOSFETs, having one latch circuit, one inductor and one high-pass filter within a voltage divider.

3. THE IDEA OF LOW VOLTAGE DC ELECTRICAL DISTRIBUTION

Low voltage DC grids are not very different from their AC counterparts. Even though some components are different in nature, characteristics, or function, the basic concept is always the same. The objective is to transport electricity through cables and components at low voltage to the end-user. The main difference between DC and AC systems are the way in which they are configured. The microgrid itself, is a distributed power system on a small scale, that is made of distributed energy sources and associated loads. Microgrids eliminate the need for connection to the main utility grid [12-15]. There are numerous advantages of DC microgrids over AC microgrids such as the absence of a skin effect, lower on-state losses as well as the ability to provide 1.41 times more power than AC, no problems with reactive power control and no proximity effect. DC also has unique issues of its own like arc interruption, fewer protection devices and is more difficult to control than an AC system. LVDC microgrids are a new concept in distribution systems. It is well suited for installation in offices that have sensitive computer loads, isolated or rural power systems. The grid that we have today in the United States of America is mostly AC and most of loads we consume using various household electronic devices which consume the energy in DC, requiring power converters to connect to the grid. If these loads are fed through the DC bus, then they will require fewer power conversion stages. Since there are fewer power conversion stages, losses resulting from conversion are also lower. Most of the resistive loads can be connected to either the AC or the DC bus.

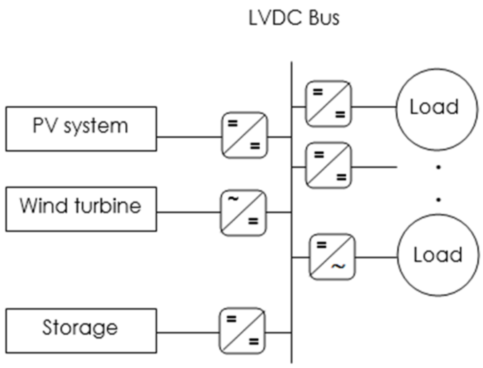

Fig. 2.1. Conceptualization of the LVDC bus microgrid system.

The above diagram shows the concept of a LVDC bus microgrid system. The active power consumed by DC loads is the same as AC loads but, there is no reactive power function in DC. A DC microgrid has a wind turbine, DC/DC converter for its battery and the solar PV. Generally, wind turbine and micro turbine uses both DC/AC and AC/DC converters but, only an AC/DC converter is used in the methodology of the latest technology.

AC power grid systems possess various advantages that are easily applicable but, certain issues like synchronization, control of reactive power and stability of the AC bus are persistent problems in the AC bus microgrid. As a LVDC bus microgrid system is small, it can neglect the loss of transmissions within the system and provides a solution to these problems. The DC distribution protection system is of considerable benefit to a LVDC bus microgrid as the fault is detected and located within the system autonomously by the protection system of the LVDC bus microgrid. Besides the benefits, DC bus microgrids also face challenges like lack of standard practices and guidelines, as well as breaking of DC arcs and DC protective devices.

A LVDC microgrid is dynamic because operation of supply and demand equipment so, suitable power-flow control, voltage regulation, protection, coordination and adequate filtering are necessary to guarantee an acceptable quality of supply. Over the last few decades, power electronics have been one of the main contributing factors behind the paradigm shift that started in the 1960s and have become increasingly power-dense while decreasing in physical volume. Such a trend was made possible, mainly, by increasing switching frequency. These days, power electronics that are very small, can be found in all types of electrical appliances that have an efficiency ranging from 50% up to 99%.

The dialog regarding voltage levels seems unending because voltage levels will always be the greatest difference between the two types of systems. Proposals about voltage level were specifically limited to voltages below 120VDC [16] [17]. Some recent pilot projects put voltages from 24VDC to 48VDC demonstrating that this may be something worthy of investigation in future work. An approach such as this one is consistent with the definition of IEC 60038 for extra low voltage to assure the protection of the user, it should be possible to have a LVDC system that runs that level of voltage even if the system had plug-in electric vehicles as well as the household's kitchen loads.

3.1. LVDC Short Circuit Currents Characteristics

A LVDC microgrid that has a new, complex topology of mixed AC and DC currents become dangerous as the system becomes more complex and new types of faults are introduced and different responses from the system are to be expected when faults occur on a LVDC system. The energy stored in the smoothing capacitors and storage devices begin to feed a large discharge current in a very short amount of transient time. This causes DC fault currents to undergo a transient discharge current that has high frequency oscillations between the smoothing capacitors and system inductances as well as short circuit current in the steady state. These transient fault currents cause a very high level of stress to the operation of protection and performance of LVDC systems [18] [19]. Characterizing LVDC short-circuits is therefore, of extreme importance. Ratings of appropriate equipment and correct protection settings, as well as selectivity, need accurate short-circuit characterization. The effectiveness of using standards that are already in place such as IEC61660 for characterizing LVDC faults will be investigated.

When an external DC fault in a LVDC microgrid begins, the charged smoothing capacitor acts instantly as a considerable source of DC fault current and begins to feed the fault. When the discharge peak current is reached, the capacitor is totally discharged and the DC terminal voltage become very small. In some cases, it is almost zero. When the anti-parallel diodes of the converter become forward biased, the VSC loses control and the IGBT switches become blocked for the purpose of self-protection. This results in the anti-parallel diodes functioning as a bridge rectifier and continuing to feed the fault during the transient. After fault occurrence, transient fault current ends, steady-state DC fault current is fed by the grid and local generation.

3.2. DC Fault Types

In General, the most common causes of short-circuiting are component failure, lighting surges, high magnitude ground fault or line to line fault, external environmental stressors such as fires or insulation failure caused by operating at excessive temperatures that result from overload stress. In LVDC microgrids, converters like VSCs IGBT-based converters are sturdier to AC faults and more sensitive to DC faults. Two types of faults may occur on the DC side. The first is an internal DC fault inside of the main converter and the other is an external DC fault, either on the converter terminals or at isolated places on the downstream DC feeders. Internal faults aren't as frequently occurring when compared to external faults [20], [21]. The most extreme external DC fault happens at the converter terminals. Remote faults on DC feeders also have a considerable impact on converter performance.

DC faults are classified as follows: Line-to-ground fault: This type of fault occurs when a positive or negative pole is shorted to the ground. In this case, the voltage of the faulted DC line drops down depending on the fault impedance. Line-to-line fault: This type of fault happens if the positive and negative DC poles are shorted. This could be the result of the DC cable insulation breaking down or a direct short circuit between the lines. Table 3.1 shows the differences between DC fault types.

Table 3.1 differences between Line-to-line and Line-to-ground fault

Line-to-line fault	*Line-to-ground fault*
The positive and negative lines are normally short-circuited whenever line-to-line faults happen.	line will be short-circuited to the ground when line-to ground faults happen.
Low fault impedance is the typical characteristic of line-to-line faults.	Both low and high impedance are the typical characteristics of line-to-ground faults.

Although overvoltage protection is vital during line to ground faults, when faults happen, the capacitor swiftly discharges to the ground [22]. Current flows through the ground and back to the non-faulted line then finally goes back to the source, causing voltage on the healthy pole to rise. Overvoltage also is concerning during the loss of an inverter. The loss of an inverter causes voltage to rapidly spike because of extreme unnecessarily high power, rapidly charging the DC link capacitors. A rectifier loss, only becomes concerning when the loss is temporary. When the rectifier abruptly returns, it causes overvoltages like an inverter loss does.

3.3. Problems Associated with LVDC Protection System

Typically, power distribution systems have not been considered important when they are viewed from the perspective of protection complexity because of the high cost as well as the radial characteristic and nature of distribution networks, that have fault current directions that are always known. The principles of operating most protection systems are based on non-unit overcurrent protection schemes in which operating time decreases as the fault current increases. Protecting LVDC distribution networks does not involve installing hardware of any kind. Additionally, interrupting DC fault current is more difficult than interrupting AC fault current. DC fault current and voltage waveforms do not have a natural zero crossing ability, so they must be forced to zero meaning that the risk of fires or arcing are expected more often with DC systems than AC because of problems that develop from forcing DC currents to zero. Because of this, standard circuit breakers and fuses have difficulty in protecting DC systems. If EMCB are going to be utilized in a DC system, a larger size and heavier weight as well as slow performance can be expected.

There is a solution. Interruption of DC fault current is possible if current-limiting fuses or current limiting circuit breakers, such as SSCBs, are used and their ratings are adjustable for application in LVDC systems [23]-[25]. These types of devices don’t require zero-crossing to extinguish DC fault arcs. Fault current will be interrupted much sooner than the time needed for fault current to reach its peak. DC fault arcs are more difficult than with AC because they must reduce the voltage across the arc by increasing its length which is accomplished by increasing the length between the two contactors and using an arc splitter to split the arc. In addition, DC short circuit profile includes two main forms. One is a high transient discharge short circuit current path and the second is a steady state short circuit current path. Transient discharge fault current can be high when compared with steady state fault current as well as causes high stress levels to network components and negatively affects protection system performance [26], [27]. Two big problems are expected to happen because of high discharging DC fault current. The first is an increase in the risk of physical damages to the sensitive equipment because of high magnitude and the second is the negative impact upon selectivity of non-unit protection. During transient current discharge, DC voltages near the fault become very small, almost zero, and sometimes the DC voltages can even become negative because of oscillation between cable inductances and filter capacitors.

4. ANALYTICAL ANALYSIS OF PROPOSED LVDC PROTECTION CIRCUIT

Observe the suggested LVDC circuit breaker design shown in Fig. 4.1 During normal steady-state operation, current flows from the source to the load passing through the IGBT and coupled inductors. An inductor is a passive two-terminal electrical component that holds electrical power in a magnetic field when electrical current is flowing through it. In this circuit, the inductor is considered as an inductive value in the distribution line.

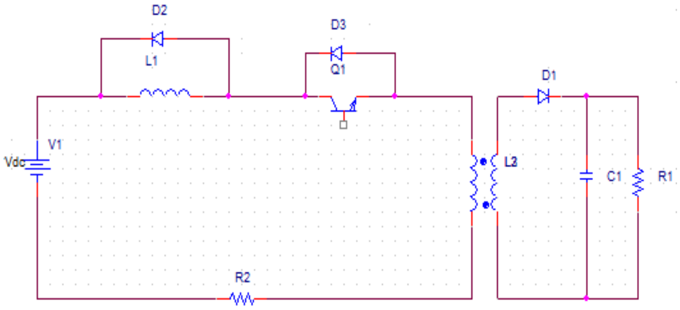

Fig. 4.1. Proposed LVDC circuit breaker mode.

Insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch. When compared with a mechanical switch, IGBT needs several microseconds to switch off the circuit. Consider the dc model of IGBT [28], shown in Fig. 4.2.

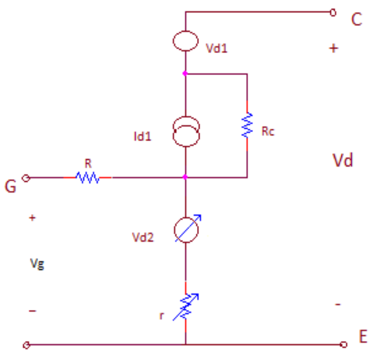

Fig. 4.2. LVDC model of IGBT.

In the model above, the voltage transfer function is expressed as:

$$V_d = \frac{\frac{mkT_o}{q}\ln\left(1+\frac{i_c}{I_o}\right)+V_{CET}}{1-\left(\frac{mki_C}{qb}\right)\log\left(1+\frac{i_c}{I_o}\right)} \tag{4.1}$$

$$\frac{V_{out}}{V_{in}} = \frac{V_{in}\text{-}V_d}{V_{in}} \tag{4.2}$$

In the above equations, the parameters are:
V_{CET} : Collector emitter voltage
K : Boltz mann constant
m : Modulation factor
T_o : Temperature of the junction of diode

V_g : Gate Emitter Voltage V_d : DC bus voltage (collector emitter voltage)

A coupled inductor transfers electrical energy between two circuits during current or voltage alteration. During the IGBT shutdown, the voltage rapidly spikes because the circuit's inductance (v=Ldi/dt). The transformer transfers voltage to the snubber circuit which absorbs and dissipates energy and is used to suppress the voltage spikes that are caused by the circuit's inductance [29]. The capacitor absorbs the voltage spikes and the resistor releases any energy stored in the capacitor. The equivalent circuit of the proposed LVDC breaker is shown in Fig. 4.3.

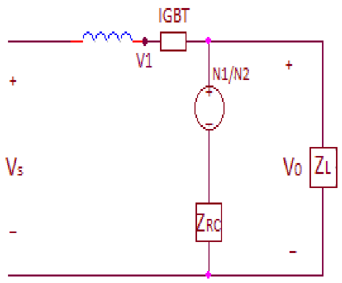

Fig. 4.3. Proposed LVDC circuit breaker mode.

V_d is the voltage for IGBT, it is acknowledged as a negligible value; so it can be ignored, in order for the transfer function of the equivalent circuit of the suggested LVDC circuit breaker is expressed as:

$$Z = Z_L // Z_{RC} \tag{4.3}$$

$$Z = \frac{Z_L Z_{RC}}{Z_L + Z_{RC}} \tag{4.4}$$

KCL at node V_1 gives:

$$\frac{V_1\text{-}V_s}{sL} = \frac{V_1\text{-}V_g}{Z} \tag{4.5}$$

$$V_s = V_1 \text{-} \frac{(V_1\text{-}V_g)sL}{Z} \tag{4.6}$$

$$V_o = V_1\text{-}V_g \tag{4.7}$$

$$H = \frac{V_o}{V_s} = \frac{Z_L + Z_{RC}}{Z_L Z_{RC} + sL(Z_L + Z_{RC})} \tag{4.8}$$

In this model, the voltage to current relation is expressed as:

$$\frac{v_s}{i_s} = sL + \frac{Z_L Z_{RC}}{Z_L + Z_{RC}} \tag{4.9}$$

The suggested LVDC circuit model (without snubber) shows the circuit with only the IGBT, without a snubber circuit. From the simulation with no snubber, it shows that there is obviously a voltage spike happening at the load during IGBT.

Parameter calculations of custom designed snubber circuit resistor and capacitor value.

Current across IGBT:

$$I_{IGBT} = \frac{V_{IGBT}}{R_{load}} = \frac{6V}{1k\,\Omega} = 6mA \tag{4.10}$$

$$R_{sunbber} \le \frac{V}{I_{IGBT}} = \frac{6V}{6mA} = 1k\ \Omega \tag{4.11}$$

Then choose the value for $R_{sunbber}$: $R_{sunbber} = 1k\ \Omega$

$$f_s = \frac{1}{T} = \frac{1}{0.1} = 10Hz \tag{4.12}$$

$$C_s \le \frac{1}{V_O^2 f_s} = \frac{1}{6^2 x 10} = 2.78\ mF \tag{4.13}$$

By calculation, when C = 1mF is used.

The power dissipates in the resistor

$$P_r = C_s . V_o^2\ x f_s = 0.36w \tag{4.14}$$

The LVDC circuit (with snubber) is the circuit model with both IGBT and snubber circuit installed. From the simulation with a snubber, fig. 4.4. illustrates how the voltage spikes are reduced to zero, because the spike is being absorbed and dissipated by the snubber. The proposed LVDC circuit breaker has a rapid switching time of 30µs. as displayed in fig. 4.5.

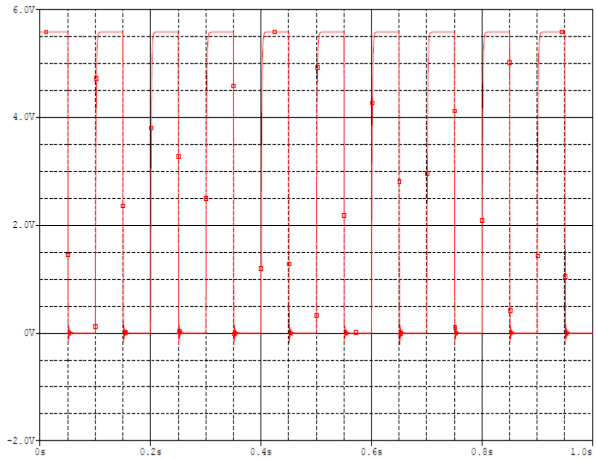

Fig. 4.4. Proposed LVDC CB model overvoltage with snubber.

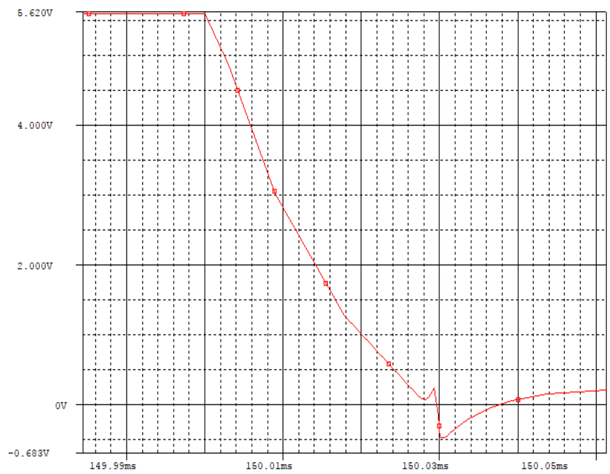

Fig. 4.5. Proposed LVDC CB model overvoltage with snubber.

5. EXAMINATION OF IGBTS FOR APPLICATION IN LVDC SSCB CONNECTED SYSTEMS

The IGBT is the most frequently used switching device for the SSCB. meaning that the reliability and durability of IGBTs are ceaselessly being confirmed by several converters that are installed in real-world power systems. Most SSCBs are based upon implementation of three semiconductor devices in some type of way. Semiconductor devices are used in SSCBs because they have extensive commercial accessibility, low power requirements for operation of gate drives as well as, high current ratings [30-33]. IGBTs have many benefits in contrast to its meagre number of drawbacks. The benefits are low switching losses, minor snubber circuitry requirements and high input impedance. Because of these things, IGBTs are reliable and durable enough to be used for the circuit breaker role. There are many topologies for the DC circuit breaker using IGBTs. Based on Fig. 5.1, the IGBT model under study comprises of an N- channel MOSFET and two BJTs, BJTs one and two. The first one is a $P^{+}N^{-}P$ BJT and the second one is an $N^{-}PN^{+}$ BJT. R1 is the resistance that is given by the drift region. R2 is the resistance given by the body region. It has been noted that the collector of BJT1 is the same as the base of the collector in BJT2 and vice versa. An equivalent circuit model of IGBT is shown below.

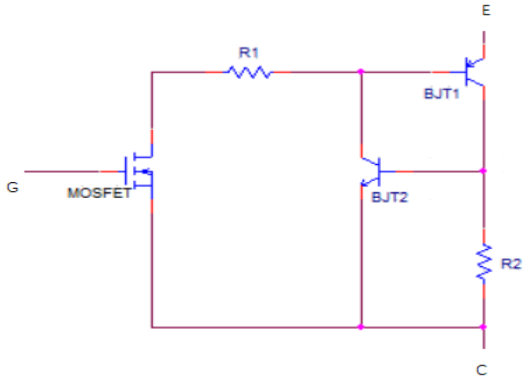

Fig. 5.1. P IGBT Model equivalent circuit.

The simulation result displays the IGBT voltage waveform in Fig. 5.2. The switching time for IGBT model shown in Fig. 5.3, is 0.593 ms. To make the switching time of the IGBT better for protecting the DC system, capacitors are introduced to the model in parallel with the resistor. Fig. 5.4, shows the improved IGBT model equivalent circuit with the added capacitors.

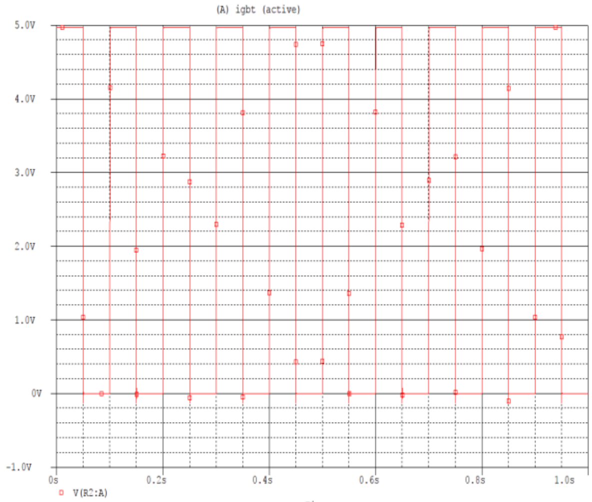

Fig. 5.2. Voltage result of IGBT model.

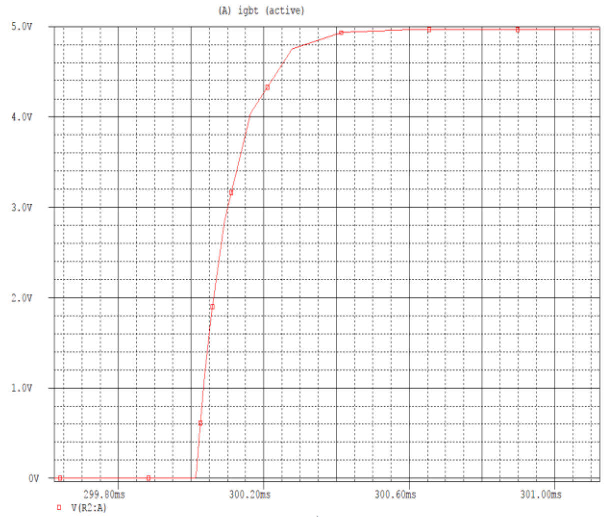

Fig. 5.3. Switching time of IGBT model.

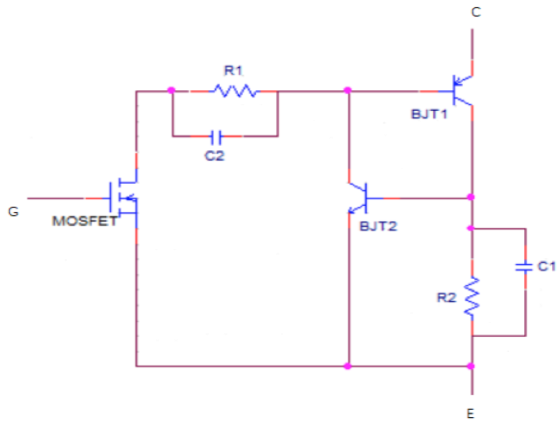

Fig. 5.4. Improved IGBT Model equivalent circuit.

Fig. 5.4, shows the improved equivalent circuit of IGBT model. The capacitor increases the speed of the switch's response. The simulation result from fig. 5.5, shows the voltage of the improved IGBT during the on-state of the IGBT. The switching time for the improved IGBT model is 0.553ms as shown in fig. 5.6 Because of the shorter response time than the original model, the improved IGBT model has been chosen for implementation in SSCB for protecting LVDC microgrids.

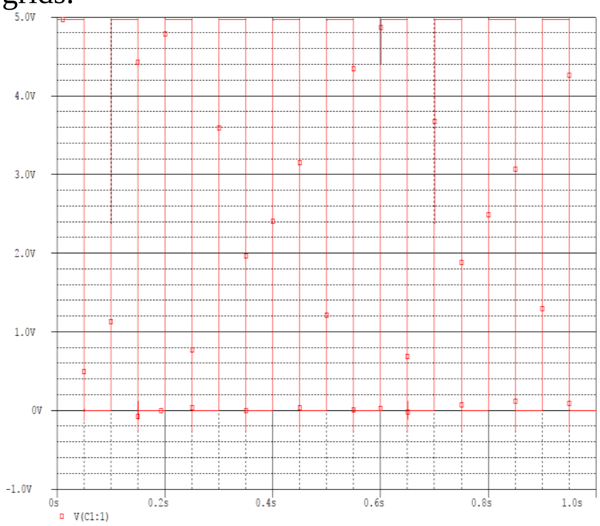

Fig. 5.5. Switching time of IGBT model.

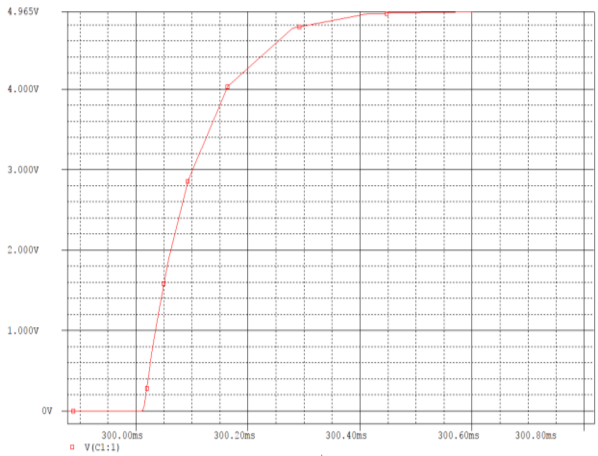

Fig. 5.6. Switching time of the improved IGBT Model.

6. MODELING THE LVDC SYSTEM UNDER STUDY

A circuit schematic has been developed for a post-regulated, isolated DC-DC converter that has two DC loads. A DC-DC converter, specifically, a unidirectional post-regulated isolated DC-DC converter is assembled from a solid-state transformer that has a controlled half-bridge on its primary side and a diode-based half-bridge on the secondary side, followed by a buck converter as displayed in fig 6.1. Another important system component to have is a voltage follower. A voltage follower delivers high impedance transformation from one circuit to another, with the purpose of preventing the source from being affected by currents or voltages that the load produces. The corresponding parameters and their respective values are displayed in Table 6.1. Both loads have an equal rating, protected by SSCBs and the load-side has freewheeling diodes that provide current continuity because of load side inductances when the load SSCB opens. With the improved IGBT model, the capacitor increases the speed of the switch's response with the improved equivalent circuit of IGBT.

Table 6.1 Parameters used in the proposed model and their values

Parameters	*Specifications*
C2,C3	10uF
C4,C5	100uF
V	60V
Z2, Z3, Z5	IGBTs(IXGH40N60)
L1	0.1H
C11	1u
L11	0.1H
R10	0.003Ω
D1-D8	Diode(D1N4002)
R13, R15, R14, R16	0.5Ω
C9, C12, C13, C16	0.01F
R8, R9	0.0015Ω
L9, L10	30.25uH
L3, L4, L12, L13	1H
C1, C14	5nF
R3, R17	1KΩ

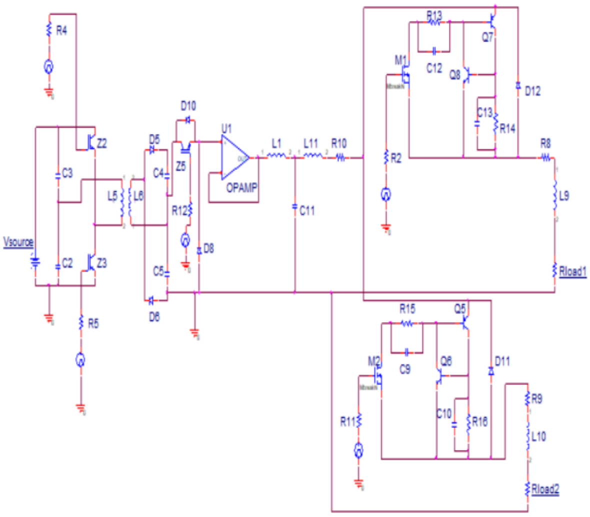

Fig. 6.1. Modified circuit schematic based on existing LVDC SSCB without snubber circuit.

Fig. 6.2. shows high levels of positively charged overvoltage during switching on times, and negatively charged overvoltage during switching off times which negatively effects equipment, causing overheating which damages electronic devices.

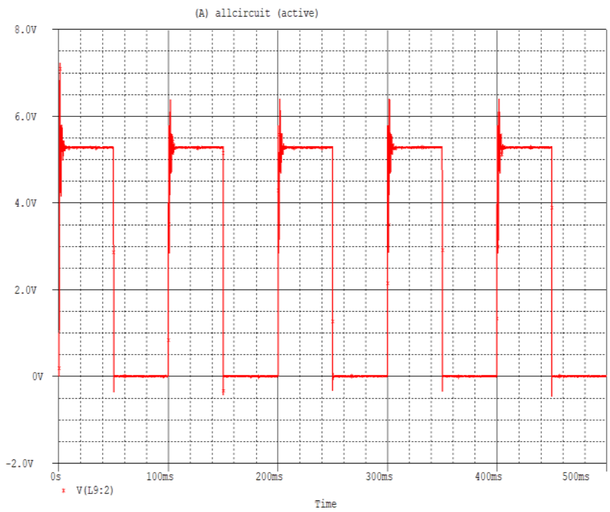

Fig. 6.2. Simulation of modified circuit based on existing LVDC SSCB model overvoltage without snubber circuit.

The equations are based on capacitor voltage and inductor currents in the distribution system as shown below and, the complete system parameters can be obtained thru consideration of the following equations.

$$i_{L_{11}} = C_{11}\frac{dV_{c_{11}}}{dt} \tag{6.1}$$

$$\frac{dV_{c_{11}}}{dt} = \frac{i_{L_{11}}}{C_{11}} \tag{6.2}$$

$$\frac{di_{L_{11}}}{dt} = \frac{V_{c_{11}} - i_{L_{11}} R_{10}}{L_{11}} \tag{6.3}$$

$$L_{11}\frac{di\,(t)}{dt} + i(t)R_{10} + \frac{1}{C_{11}}\int i(t)dt = V_{C_{11}} \tag{6.4}$$

The Laplace transform

$$I(s) = \frac{\frac{V_{c11}}{sl_{eq}} + I_1}{s + \frac{R_{10}}{L_{11}} + \frac{1}{sl_{eq}}} + \frac{\frac{V_{c11}}{L_{11}} + sI_1}{s^2 + \frac{R_{10}}{L_{11}}s + \frac{1}{L_{11}C_{11}}} \tag{6.5}$$

$$i(t) = e^{-0.015t}\left[i(0)\cos 3162t + \left(\frac{V_{c11}}{wrL_{11}} + \frac{0.015i(0)}{3162}\right) \times \sin(3162t)\right] \tag{6.6}$$

Where:

$$\propto = \frac{R_{10}}{2L_{11}} = \frac{0.003}{2\times0.1} = 0.\ 01$$

$$\omega_0 = \frac{1}{\sqrt{L_{11}C_{11}}} = \frac{1}{\sqrt{0.1\times1\times10^{-6}}} = 3162$$

$$\omega_r = \sqrt{\omega_0{}^2 - \propto^2} = 3162$$

The following schematic of proposed LVDC SSCB include improved IGBT model and custom design snubber circuit in each load. The parameters of snubber circuits were previously discussed.

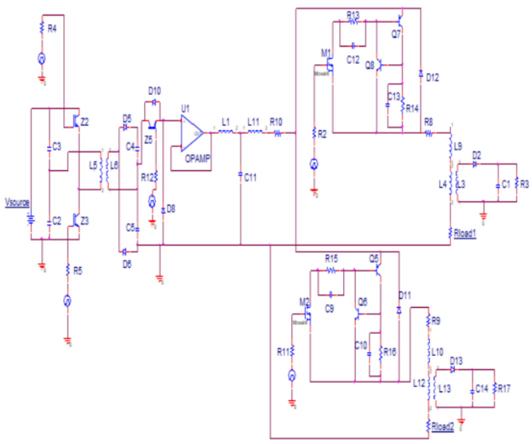

Fig. 6.3. Circuit schematic of proposed LVDC SSCB with snubber circuit.

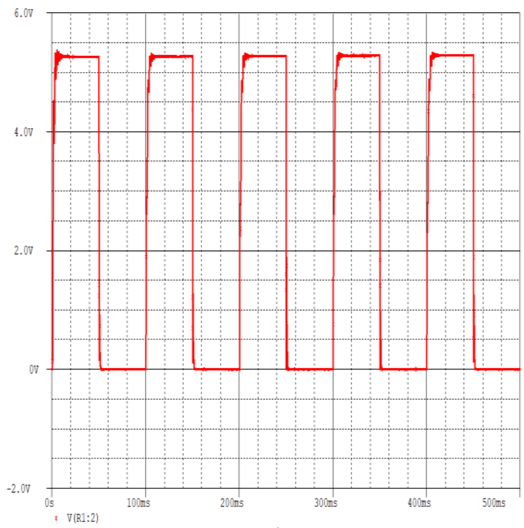

Fig. 6.4. Protected SSCB model with snubber circuit.

Fig. 6.4. shows a simulation of a circuit schematic of proposed LVDC SSCB with a snubber circuit. When compared with Fig. 6.2, which is without a snubber circuit, an extremely small overvoltage during switching on times, and negative overvoltage is reduced to zero during switching off times. The custom designed snubber circuit suppresses the voltage spikes caused by the circuit's inductance when operation modes switch. Fig. 6.5. displays the switching time of the IGBT, the time duration is preformed faster than the existing IGBT model, as discussed above.

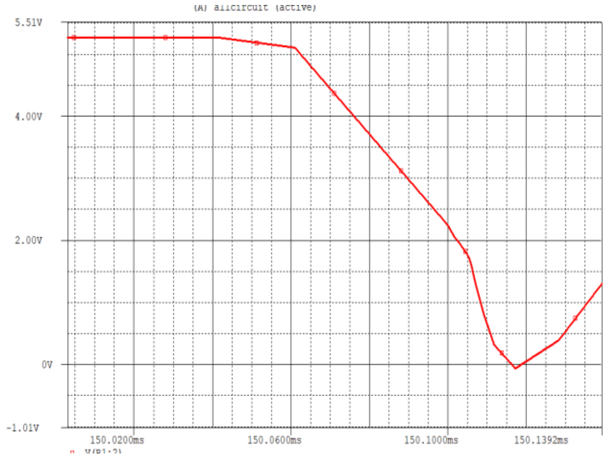

Fig. 6.5. Proposed SSCB model switching time.

7. CONCLUSION

This paper offers an illustration of the workings of SSCBs in LVDC applications. The motives for the selection of SSCBs are discussed along with the design of the suggested LVDC SSCBs. Advancement in semiconductor technologies have experienced substantial improvement these last few decades and many devices have been designed. In the future, these technologies are only going to get even better. SSCBs are swift to respond to faults experienced in the LVDC grid. This makes the DC power system of the future a more reliably sturdy and advanced system that is much better protected than the systems already in place today. Further studies on the use of different semiconductor devices such as IGCTs and GTOs enables greater understanding of the difference between the systems of the past and the modern systems of today as well as future systems as new technologies become available. This will enable protection of many different configurations of LVDC distribution systems and microgrid applications.

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