

Novel Modeling of a Fast DC Breaker for a VSC-HVDC Transmission System Protection

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Abstract

The inability to quickly isolate the faulty sections of the direct current (DC) network damages the converters and the transmission system. Further delay in fault interruption can be escalated to the generation system thus shutting down the whole power system. Currently, Voltage Source Converter-High Voltage Direct Current (VSC-HVDC) systems provide the best mode of bulky power transmission over long distance. Though VSC-HVDC have their own internal protection, they still suffer from short-circuit faults especially on the DC side hence requiring a novel fast DC breaker. The novel design of the DC breaker in this paper utilizes a systematically calculated mutual inductance to divert the energy generated during fault to resistive element on both sides of the DC breaker thus, preventing the transient voltage and backward current generated at the time of clearing the fault. The major challenge for DC breaker is that current is not alternating inferring that it has no natural zero current occurring point. Thus, the current has to be artificially forced to cross a current zero point so that the fault can be easily interrupted. This study aims at reviewing the currently available DC breakers with a fault clearing time of 5ms by modeling a novel fast DC breaker therefore, providing the best possible protection against short-circuit faults on VSC systems. The results indicate that the proposed DC breaker model has a fault clearing time of 1ms. This is a major contribution towards the development a fast DC breaker.

Keywords: Novel fast DC breaker; VSC-HVDC transmission system; Short circuit faults; Zero current crossing point

Introduction

The currently existing DC breakers are not fast enough to provide adequate protection for VSC-HVDC systems. This exposes converters and transmission system to serious risks under short-circuits faults. It is particularly disastrous for DC faults that rely on AC breakers for isolation of the faulty section of the network. Despite the fact that HVDC breakers have their internal protection mechanism, it has been proven that it is not sufficient to interrupt the fault as quickly as possible, thus necessitating the design of a novel fast DC breaker. Additionally, the growth of multi-terminal HVDC systems and emergency of wind power that has intermittent characteristics justify better protection management of the VSC-HVDC system [1].

VSC-HVDC systems are highly vulnerable to DC short-circuit faults. The ability of the AC breakers to interrupt faults on the DC side is limited by the slow speed of clearing the fault and in many instances a fault on the DC side is not discriminated by the AC breaker thus resulting to isolation of the whole network. This repeated operation reduces the useful life span of the breaker in addition to loss of revenue. One major advantage of AC breakers is that they have the ability to easily interrupt fault during the zero current crossing point, a sequence that is repeated twice every cycle though the speed of interruption is too slow for AC breakers. Fault interruption using DC breaker is a challenging task because it has no zero current crossing point, has small inductance on DC side of the system and the rate of rise of DC fault current is considerably high necessitating a very fast interruption technology [2]. Therefore, to quickly interrupt DC fault, a fast DC breaker is essential so as to clear the fault in less than 5ms. The most recent DC breaker was proposed and has a fault clearing time of 5 ms [3]. Further, DC circuit breakers for high voltage applications are not commercially and widely available today though various attempts by researchers to develop a fast DC breaker has been ongoing [4].

Globally, power grids are interconnected to provide significant

technical, economic and environmental advantages, such as pooling of large power generation stations, sharing of spinning reserve and use of most economic energy resources in addition to taking power where it is needed most. This need has necessitated the development of multi-terminal systems which are attractive for renewable energy interconnects. The multi-terminal system utilizes more than one converter and it is only fair to provide fast and excellent protection system otherwise in the event of system malfunctioning; the high current magnitude generated may cause serious damage to the converters and the transmission system. The VSC-HVDC system utilizes the insulated gate bipolar transistors (IGBT) for switching purposes. These devices are known to have fast switching operation and have high efficiency that fast DC breakers possess. The modern HVDC system uses VSC which act as a constant current source and has capacitors to store energy with very little need for large filters and reactive power supply. Further, it has the ability to generate its own reactive power consequently controlling its active power and voltage effectively. This is in contrast with the current source converters (CSC) which is seldom used in the modern converter systems.

VSC-HVDC system has the potential to change the direction of power flow by changing the direction of the current while for a CSC, the DC voltage polarity have to be altered a task not easily achievable. It therefore shows that, a fast DC breaker is a promising technology

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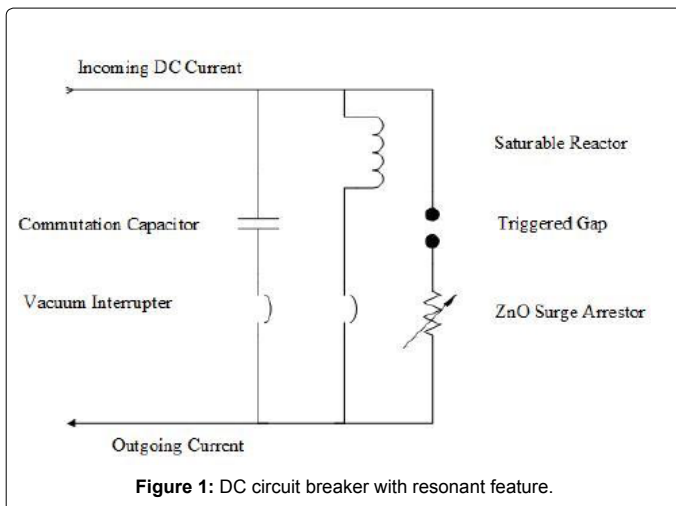
for future VSC-HVDC system protection against the common short-circuits faults.

Challenges in HVDC circuit breaker design

AC breakers have the potential to interrupt fault twice every cycle during the current zero crossing point a characteristics deficient in DC breakers. The DC current in DC breakers has no current zero crossing point thus making it difficult to interrupt the fault [5]. The current zero crossing for DC breakers has to be artificially created to forcefully interrupt the current at the occurrence of the fault. One of the traditional approaches in achieving current zero point during the fault is the use of resonant current. Such a DC breaker design is shown in Figure 1 [5].

Under fault condition, the DC breaker receives a signal from a relay with instruction to trip the breaker. This results into opening of the DC breaker and discharging the stored energy into the inductor through the triggered gap. This operation creates a current zero crossing point a scenario necessary for fault interruption. The energy absorbed by the inductor is dissipated to the surge arrester and converted into heat. The surge arrester is the absorbing agent for energy stored on the line while the resonant circuit creates the much needed current zero crossing point. The inductive reactance assists in maintaining the rate of current change ($\frac{di}{dt}$) at a controlled level and the high pass filter circuit regulates the recovery voltage [5]. In the event of short-circuit fault, HVDC breakers have short interruption time thus resulting to high ($\frac{di}{dt}$) that is detrimental to the converter valves. The surge arrester has limitations such as the energy stored deteriorates its life span while the solid state valves are sensitive to reverse voltage spikes caused by switching transients. The challenges can be overcome by designing a novel fast DC breaker that incorporates passive components with freewheeling diodes on both sides of the IGBT to safeguard it against voltage spikes.

At present, VSC-HVDC technology is widely utilized around the world because of its many advantages compared to CSC-HVDC system. VSC-HVDC systems finds application in transmission of highvoltage over long distances and is mainly used for wind farm integrations, while the AC grid interconnections is used in power supplies for isolated islands or weak power grids [6,7]. VSC-HVDC systems are convenient for wind power transmission given that most of the wind farms are located in the offshore far away from the load



centers. In order to effectively limit the fault current under short-circuit faults in DC circuits, the traditional thyristors based on HVDC uses large inductor as DC filters [8]. However, the scenario is difficult in VSC-HVDC because of the sharp increase in fault current levels. Under fault, the capacitors on the DC side of a VSC discharges and quickly causes the voltage to decrease to zero. Then all the diodes which are inversely parallel with the controlled devices such as IGBT and gate turn-off (GTO) devices), begin to conduct. Due to the lack of a reverse voltage provided by the capacitors, the AC grid continue to feed the fault current through the uncontrolled rectifiers, which damages the voltage source converters and their valves [8]. Therefore, a quick and effective DC breaker is necessary to enable protection of the VSC-HVDC system especially the DC faults that can cause the collapse of the whole network when protected by AC breakers.

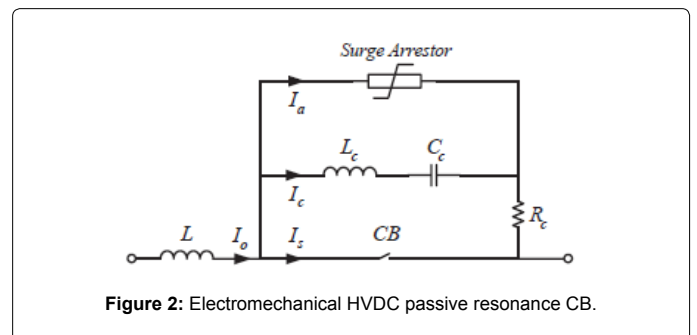
Types of DC circuit breakers

Currently, there are four types of DC breakers; these are

- The electromechanical DC breaker,
- The solid state breaker,
- The hybrid breaker,
- The new design of solid state breakers.

Electromechanical resonance CB: The electromechanical resonance CB is classified into passive and active resonance. The former is an old technology and was initially developed for CSC-HVDC systems [9]. Figure 2 shows an electromechanical HVDC passive resonance circuit breaker [10].

The nominal current path is usually where the DC current (I_o) passes through and the switch (CB) is closed during the normal operation. The commutation path consists of a series resonant circuit with an inductor and a capacitor that provides the condition suitable for creation of zero current point necessary for DC breaker fault interruption. The surge arrester is an absorption element for energy generated during fault where interruption is required, to enable current oscillation to occur between the nominal and the commutation path at the natural frequency ($\frac{1}{\sqrt{LC}}$). Thus, zero current crossing occurs when the amplitude of the oscillating current is larger than that of the input current and the switch can now interrupt the current in the nominal path. Consequently, Current (I_o) will continue to flow and will charge the capacitor, however, if the capacitor voltage exceeds a given value, which is chosen to be the voltage capability of the DC breaker, the energy absorption path (surge arrester) will act resulting to current decrease thereby providing an ideal zero point for current interruption. Electromechanical HVDC circuit breakers have been in use for many years and are available up to 500 kV, 5 kA with a fault-clearing time of the order of 60-100ms [4].



To understand the interruption process it is necessary to analyze the current equation during the process. The differential equation during fault interruption can be written as below:

$$L_c \frac{d^2 i_s}{dt^2} + \left(R_c + \frac{\partial u_{arc}}{\partial i_s} \right) \frac{d i_s}{dt} + \frac{1}{C_s} i_s = \frac{I_o}{C_c} \quad (1)$$

$$i_s = I_o \left(1 + e^{\frac{1}{2L} \left(R_c + \frac{\partial u_{arc}}{\partial i_s} \right) t} \cdot \sin \omega_c t \right) \quad (2)$$

Where, $\omega_c = \sqrt{\left(\frac{1}{L_c C_c} \right)}$

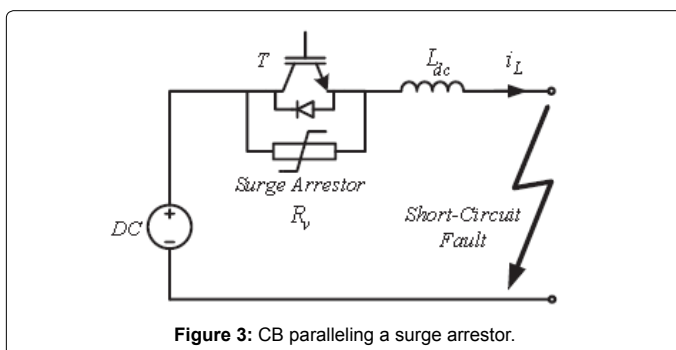
If, $R_c + \frac{\partial u_{arc}}{\partial i_s} < 0$ then, i_s will oscillate with increasing amplitude. The first zero crossing of current will be enough for the breaker to interrupt it being the ideal fault break off point for the DC breaker.

The other classification of electromechanical DC breaker is based on active resonance CB also known as two stage interruption method [4]. The only remarkable difference with the passive CB is that the resistor is used as an energy absorption element as opposed to the surge arrester in passive resonance CB. Surge arrestors are not as rugged as resistors when subjected to frequent short-circuit faults thus are not long lasting and reliable. They too are costly as compared to resistors and their rate of energy absorption under short-circuit fault is slow. This slowness in energy absorption also slows down the rate of fault clearance under fault and can be catastrophic to converters and the transmission network.

Solid state circuit breakers (SSCB): The SSCB's have ultra-switching speed thus are the best for fault interruption in DC circuit. SSCB research has been ongoing and some new contributions are found [11,12]. Also, in literature, two topologies for SSCB are discussed [12]. These are where the CB is paralleling a surge arrester and the other is a CB with a freewheeling diode. Figure 3 shows a CB paralleling a surge arrester [9].

SSCB employing a parallel surge arrester utilizes an IGBT for quick switching operation. Under normal operation, current flows from the source to the load through the IGBT however, when a fault is detected, the semiconductor switches off. Then the load current commutates to the surge arrester. Also, the surge voltage across the IGBT (T) is limited to the clamping voltage of the surge arrester. Clamping voltage of surge arrester is assumed as $V_{dc} + V_{margin}$. It is also assumed that the impedance of the fault point is slightly small. When IGBT turns off at time $t=0$.

V_{margin} is applied to L_{dc} so the inductor current can be calculated as follows:



$$i_L = I_o - \frac{V_{Margin}}{L_{dc}} t \quad (3)$$

Where I_o is the amplitude of the fault current at $t=0$. The time to turn off the fault current T_{open} is derived as follows:

$$T_{open} = \frac{L_{dc}}{V_{margin}} I_o \quad (4)$$

The energy absorbed by the surge arrester can be given by:

$$W_R = \left(\frac{V_{dc}}{V_{margin}} + 1 \right) \frac{1}{2} L_{dc} I_o^2 \quad (5)$$

V_{margin} is usually much smaller than V_{dc} in high power applications in order to suppress the voltage across the IGBT and to reduce its conduction loss. In such a case, the term in the parenthesis of equation 5 becomes large. The energy dissipated is therefore given by $\frac{1}{2} L_{dc} I_o^2$ and the more the energy in IGBT is suppressed, the more capacity the surge arrester needs to accommodate [11].

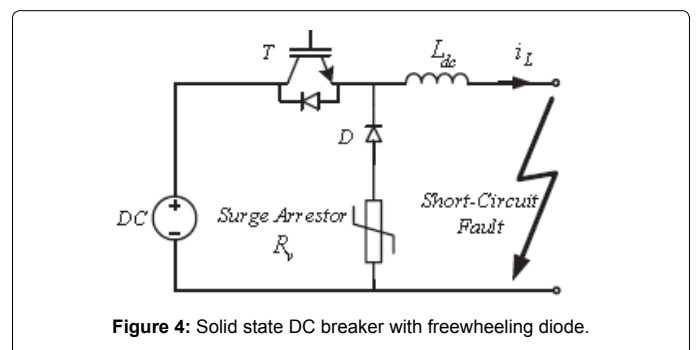
The other SSCB topology employs CB with freewheeling diode. The purpose of the diode is to bypass any reverse voltage impulse thereby protecting the IGBT against voltage spikes mostly known to damage the IGBT valves. This kind of arrangement reduces the energy absorbed in the SSCB with suppressing the surge voltage across the IGBT. Equation 6 below shows the energy absorbed is less for CB with freewheeling diode as opposed to CB paralleling a surge arrester. This is a confirmation that CB employing freewheeling diode is able to quickly dissipate the little energy absorbed and swiftly dissipate it as heat thus providing the much needed fast DC breaker operation.

$$W_R = \frac{1}{2} L_{dc} I_o^2 \quad (6)$$

A circuit configuration of the solid-state dc circuit breaker using a freewheeling diode is shown in Figure 4 [9].

Hybrid DC breakers: As the name suggest, hybrid DC breakers employ both mechanical switches and the solid state devices for switching operation. The technology has two major advantages one being low losses because of the mechanical switches utilized while the second is the ultra-switching speed due to the application of the solid state devices. The application of hybrid DC breaker continues to attract a lot of attention [13]. Further, ABB and ALSTOM have developed Hybrid HVDC CB prototypes with some considerable improvements [14-16].

Mechanical DC breakers operate at less than 100 ms however, with the recent development in semiconductor technology companies such as ABB have their HVDC CB with ability to clear faults within 5 ms [17].



The new solid state DC breaker (NSSDCB): The NSSDCB was developed by Negari [3]. He came up with several topologies which mainly use the solid state devices or a combination of solid state devices and mechanical switches. Normally, the reaction time upon detection of a fault depends on the type of the DC breakers selected, location of the fault and the mechanism for energy absorption and dissipation. The speedy operation is critical in isolation of the faulty network thus allowing only the healthy network to remain in operation. The converter would be able to continue with its normal operation as soon as the fault is cleared [18]. Notably, the main challenge with VSC-HVDC-CB is the absorption of the energy generated during the fault. This energy stored in the transmission line has to be dissipated as heat as quickly as possible. However, upon occurrence of the short-circuit fault, the current magnitude rises rapidly until the time that the CB disconnects the power line from the converter. During this delay time before the breaker responds by either discriminating the fault or fully isolation of the network, can cause serious damage to converter valves and the transmission network.

Normally DC breakers have challenges with fault interruption because they do not have the naturally occurring current zero point like it happens with the AC breakers. Many of these breakers have been known to rely on resonant circuit to create zero current crossing point and also use the surge arrestors to absorb the energy generated at the time of fault. The new DC breaker utilizes the mutual inductance instead of surge arrestors to absorb the energy and dissipate it to the resistive element as heat. Also, a diode is included in the circuit to bypass any reverse voltage impulse thus protecting the IGBT. This relatively new breaker has the ability to clear the fault in 5ms thus necessitating a design of a quicker DC breaker that will avoid large di/dt current. The Figure 5 shows the new solid state DC breaker [3].

The use of mutual inductance eliminates the need for surge arrestors because any abnormal condition (sudden impulse) in either current or voltage can be suppressed by the high pass filter (R_2, C_2). Under normal operation, the current flowing through R_2 is insignificant and the resistor only operates under short-circuit fault to dissipate the energy absorbed by the mutual inductance.

Proposed Novel Fast DC Breaker

As earlier discussed, four types of DC breaker have been developed over the years though not all are commercially available [11]. Further, the latest developed DC breaker has a fault clearance time of 5ms which is still not fast enough to provide enhanced protection of the converters valves against short-circuit faults [3,17]. Traditional DC breakers such

as electromechanical relies on resonant circuit to force current to zero crossing point at the time of fault clearance while others relies on charged capacitor bank that is discharged in an oscillatory behavior resulting to zero current crossing. This is an ideal condition for fault interruption. It is noted that, at the time of fault interruption, a lot of arc is generated by the AC breakers. The quenching media traditionally used are air, oil or the SF6 gas. However, these traditional cooling media have proved ineffective in DC breakers. For DC breakers, the energy generated at the time of fault is absorbed by the ZnO arrestors for electromechanical breakers while the solid state breakers utilize the mutual inductances. The issue with all these breakers is the slow response time, high power losses, partial protection of the IGBT and bulkiness. To overcome these challenges, a novel model is developed in MATLAB and utilized in this study as shown in Figure 6.

The novel fast DC breaker proposed in this study is developed through the act of balancing the amount of energy absorbed at the time of fault event and speedy dissipation of the same energy through a high pass filter with a resistive element. Further, the freewheeling diode is included to protect the IGBT against voltage spikes; in addition, two diodes with high pass filter connected on both sides of the IGBT to safeguard the IGBT against overvoltage. Besides, equation 6 shows that, the energy absorbed by the mutual inductance is less for a CB connected in parallel with the freewheeling diode. This is critical because the greater the amount of energy absorbed, the longer it takes to dissipate it as heat, thus negatively affecting the DC CB response time. The double protection of the proposed DC breaker improves the speed of the breaker operation during fault by providing quick response time. This enhanced design has reduced the DC breaker operation to 1ms. This is a great stride from the previously available DC breakers whose fault clearance time is in excess of 5ms [16].

Comparison of the DC Breakers Technologies

The four types of DC breakers discussed in this study can be summarized into five categories, namely:

- Interruption time
- Power losses
- Voltage rating
- Current rating.
- Cost

The relationships of the four types of the DC breakers can be found

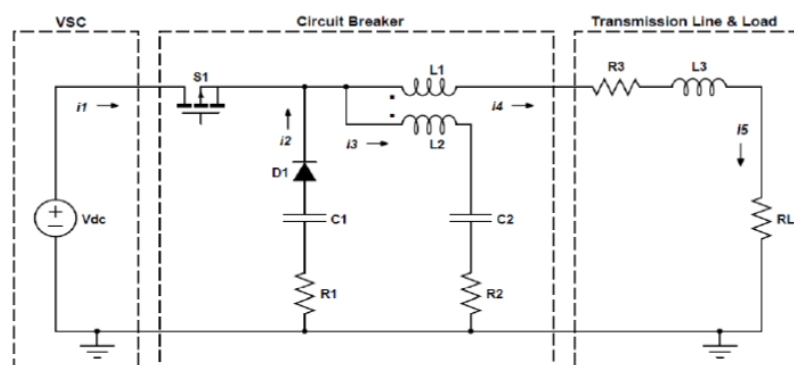


Figure 5: The new solid state DC circuit breaker.

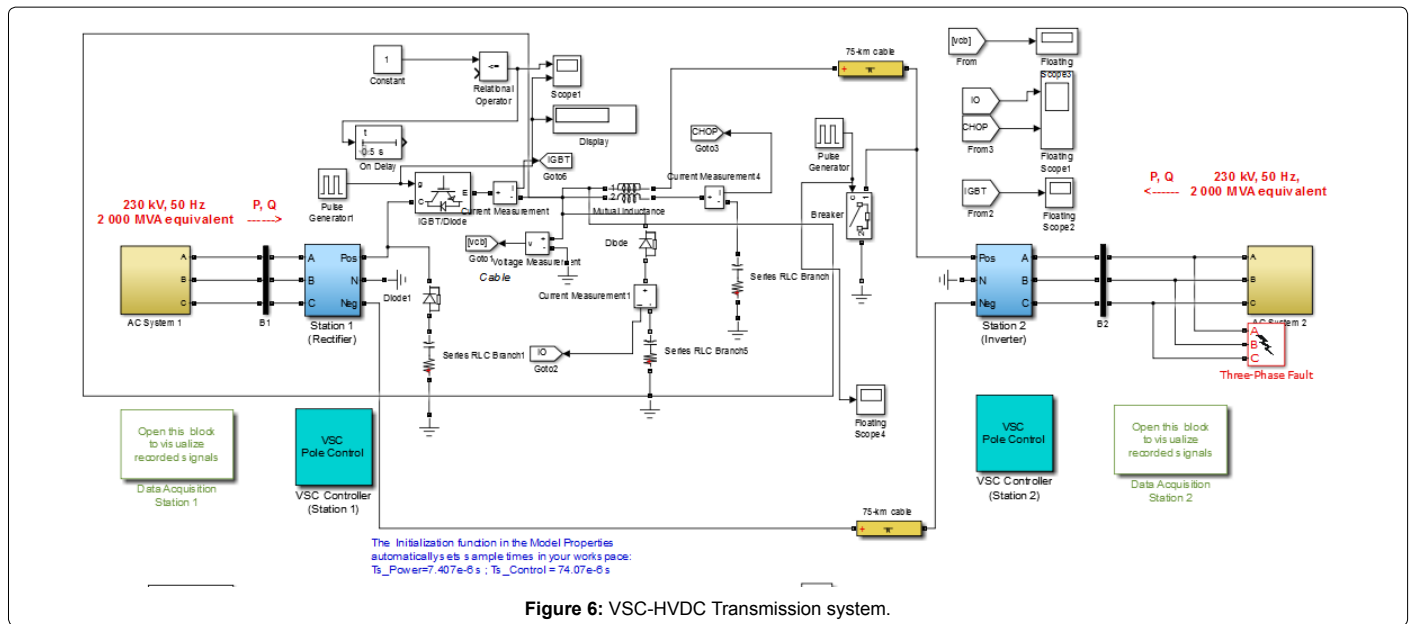


Figure 6: VSC-HVDC Transmission system.

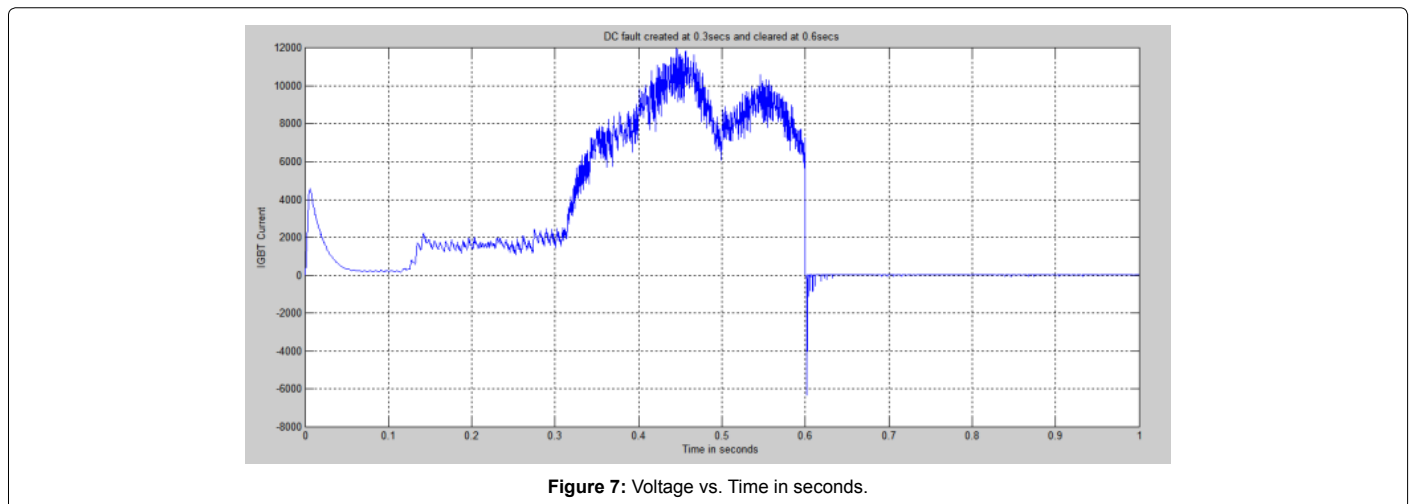


Figure 7: Voltage vs. Time in seconds.

[11]. The novel fast DC breaker developed in this study has many advantages compared to other types of DC breakers. The high voltage across the inductor causes overvoltage which is a good ingredient for fast demagnetization process thus limiting the peak current to low levels. These characteristics further limit the damage that can be exposed to converters valves under fault. Although the DC breaker has many advantages, it has higher VSC station power losses and is vulnerable to reverse voltage spikes generated at the time of current disruption. The power loss occurs during the on-state conduction because the resistance of the new solid state DC breakers is negligibly small in the range of tens of milli ohms. Though the cost of the novel fast DC breakers seems prohibitive, in reality it is not because the quick switching of the IGBT provides excellent protection against faults on the converter and the DC transmission network.

Results Simulation

In order to find the fault clearance time for the proposed novel fast DC breaker, modification of the VSC-HVDC model in Matlab was carried out. Figure 7 shows the IGBT voltage characteristics under

short-circuit fault. A short-circuit fault was created at 0.3seconds and at 0.6 seconds, the relay sent a signal to the DC breaker to operate and isolate the faulty section of the network. It is noted that the simulation displays some on-state losses even under normal operation due to the use of IGBT. In this study, the focus was about fast switching operation and based on that criterion, IGBT was selected.

Figure 8 shows that a DC fault was created at 0.3 secs and the DC breaker operated at 0.6 secs. Though the DC breaker interrupted the current at 0.6 seconds, power oscillations continued up to 0.601 seconds where the power oscillation dies out. This is an indication that the modified HVDC Matlab model that incorporates high pass filter on both the rectifier and inverter side of the converter prevents voltage spikes against damaging the IGBT thus enabling very fast operation by the novel DC breaker. In this study, a fault clearance time of 1ms was achieved. This is a great strides in the development of fast DC breaker ever been developed. As rightly put, the fastest DC breaker developed has a fault clearance time of 5ms [3,17].

Figure 9 shows the behaviour of power when a DC fault is initiated. A

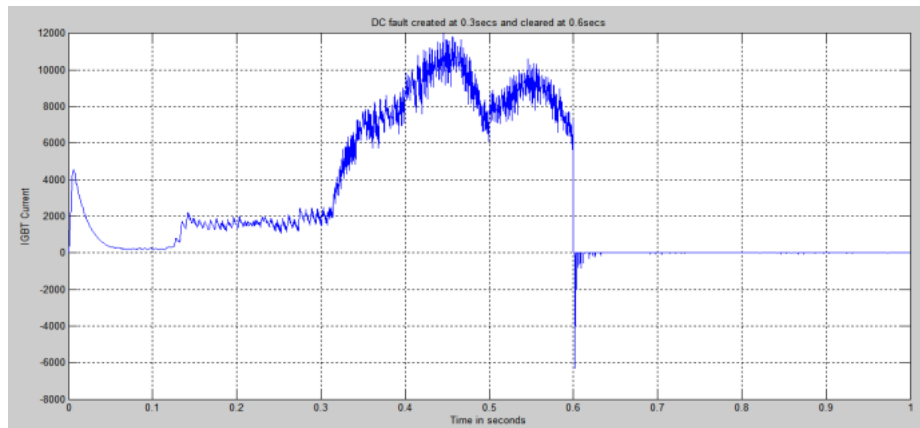


Figure 8: IGBT current vs. time in seconds.

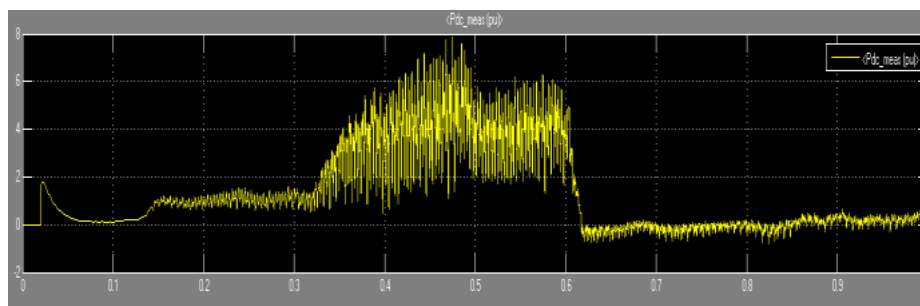


Figure 9: Characteristics of DC power vs. time.

fault occurred at 0.3s and the IGBT operated at 0.6s. You will find that during the normal operation between 0-0.3 s power losses should practically be zero however, there seems to be power losses due IGBT utilizing transistors which usually have on-state losses occasioned by swift switching speed. It is also seen that at the time of DC fault occurrence, power losses increases rapidly until the IGBT completely interrupts the fault. One important contribution in this study is that the DC fault was cleared at 1ms. This is the fastest fault clearing time ever been achieved.

Conclusion

The relationship and trends of the four types of DC breakers currently available are compared against a novel fast DC breaker developed in this study. The currently existing fast DC breaker has a fault clearing time of 5ms, however, the novel fast DC breaker developed in this paper has a fault clearing time of 1 ms [3,17]. The development of a novel fast DC breaker is an important invention particularly when the global trend is focused on greater integration of renewable energy with dynamic features. Such fast DC breakers are not commercially available thus making the findings of this paper a great milestone in the development of a fast switching device.

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