SMART LOW VOLTAGE AC SOLID STATE CIRCUIT BREAKERS FOR SMART GRIDS

Abstract: The solid state circuit breaker (SSCB) is a device used in the power system in order to provide protection when a short circuit or fault current occurs. The objective of this paper is to study and implement a smart prototype of SSCB for smart grids. The presented SSCB is controlled through the current/time characteristics of that used in the conventional mechanical circuit breakers in addition to limit the high fault current levels (fault current limiter) especially with the proliferation of the distributed generation and the associated fault current level increase. In this paper, the principle of operation of the mechanical circuit breakers (MCB) and their classifications are introduced, and switches used in the design of SSCBs are presented. Simulation of SSCB is carried out to study its feasibility and performance in the case of various operating conditions. Then, a hardware prototype of SSCB using IGBTs devices is constructed and tested to elucidate the proposed concept.

I. INTRODUCTION

In earlier days, a fuse and a switch connected in series are used in order to protect the operation of power systems from a fault condition. However, such as a mean of control presents two disadvantages. First, the fuse should be replaced after fault interruption. Fuses also cannot interrupt the high current in the modern high-voltage, and high capacity circuit. In past years, the mechanical circuit breaker was the common solution to protect the power systems; on the other hand, mechanical circuit breakers have a bouncing problem and arcing phenomena which makes it unreliable and inefficient. This is the reason why scientists and engineers faced challenges of integrating new generation into existing power systems that can detect and clear faults faster with no arcing and bouncing problems such as noises and wear. Solid state circuit breaker (SSCB) is the modern transfer model of the mechanical circuit breaker [1-3]. Utilizing a high power SSCB offers a feasible solution to the transmission and distribution system problems caused by high fault current [7-11][15][18]. SSCBs can limit the fault current and inrush current; it can also reduce the switching surge and improve the power quality for the un-faulted lines[4]. There are mainly four types of faults [4]: Line-to-Ground fault whereas in this type of Electrical fault, all three sequence components (positive, negative and zero sequence components) are present and they are equal to each other. In case of isolated neutral connection to the generator, there would be no return path for the current; hence the fault current will be zero, (2) Line-to-Line fault: these are unsymmetrical faults as they give rise to unsymmetrical currents (current differs in magnitude and phase in the three phases of power systems), Line-to-Line-Ground fault: these faults are of unsymmetrical nature. In this case, negative and zero sequence faults are in opposition with positive sequence components, Three phase fault: It is also called symmetrical fault. This type of faults occurs very rarely but more severe compared to previous ones. In these faults negative and zero sequence component currents are absent, whereas positive sequence currents are present. The objective of this paper is to study and implement a smart prototype of SSCB for smart grids. The presented SSCB is controlled through the current/time characteristics of that used in the conventional mechanical circuit breakers in addition to limit the high fault current levels (fault current limiter) especially with the proliferation of the distributed generation and the associated fault current level increase. In this paper, the principle of operation of the mechanical circuit breakers (MCB) and their classifications are introduced, and switches used in the design of SSCBs are presented. Simulation of SSCB is carried out to study its feasibility and performance in the case of various operating conditions. Then, a hardware prototype of SSCB using IGBTs devices is constructed and tested to elucidate the proposed concept.

II. MECHANICAL CIRCUIT BREAKERS

A. Circuit Breaker Operation Principle

Mechanical (classical) circuit breakers are devices used in order to provide the protection of the power system from any faults. As shown in Figure 1, the classical circuit breaker consists of fixed and moving contacts, called the electrodes. These contacts can be turned OFF, or ON manually whenever it is desired, or automatically when it is controlled by another circuit or when a short circuit appears. These electrodes usually remain closed to allow the passing of the current, and when a fault occurs, the trip coils of the circuit breaker will energize, and the moving contacts will pull apart causing the circuit breaker to open. Subsequently, an arc occurs, which initially has a little impact on the current by delaying the current interruption process and generating the heat which might cause a system damage or to a damage in circuit breaker itself[1][17][23].

B. Arc Phenomena

When a fault occurs, a high current will flow through the electrodes. The contacts of the circuit breaker start to separate and cause the area between the two contacts to decrease. The heavy fault current will lead to an increase of the current density, and hence the rise of the temperature (heat). The heat produced in the medium, which can be either air or oil, will result in the ionization of the air, or to vaporization and ionization of the oil where they will act as conductors. Therefore, an arc will occur between these contacts as shown in Figure 2 due to the potential
difference that provides a resistive arc path. Then, the current would remain uninterrupted as soon as the arc disappears. The arc resistance depends on; first, the arc resistance increases with the arc length. Second, decreasing the number of the ionized particles in the arc between the two contacts will increase the arc resistance. Third, decreasing the cross section area of the arc will increase the arc resistance. Hence, a high arc resistance means a low current flow between the two electrodes[3][14][27].

C. Principle and Method of Arc Extinction

In order to reduce the arc, we can decrease the distance between the two contacts in such a way the potential difference becomes inadequate to maintain the arc. But this process works only in the low-voltage system where the long-distance separation is not required. We can also reduce the arc produced by the ionized particle between the two contacts by cooling or removing the particles from the medium that separates the electrodes. To extinguish the arc, there are different methods that can be used. They can be either in the high or in the low resistance methods:

• **High Resistance Method:**
  This method is done by increasing the resistance of the arc with time leading to the decreasing of the current produced between the two contacts. This method causes the energy loss that is dissipated from the arc. Therefore, this approach can be used for low capacity AC and DC circuit breakers where energy losses are not high. The arc resistance may be increased by: Lengthening the arc, Cooling the arc, Reducing X-section of the arc, and Splitting the arc.

• **Low Resistance Method:**
  This method is used in the AC circuits only. The arc resistance is kept low until the current reaches zero, such that the arc resistance can be prevented from the re-striking voltage between the two contacts[4][14][22][34]. The medium between the two electrodes includes ions, so that it has a small dielectric strength that can break down by increasing the re-striking voltage (contact voltage). However, in this case the arc might persist for another half cycle; in order to avoid this problem, the dielectric strength should increase faster than the voltage across the electrode, and also after the zero current crossing. As a result, the arc would fail to re-strike and the current will be interrupted. Reducing the arc can be achieved by making the ionized particles to recombine into neutral molecules, or by replacing them by un-ionized ones[4][14][22][34]. The most important issue in AC circuit breakers is to de-ionize the medium between the two contacts rapidly; and instantly after the current goes to zero. Hence, the re-striking voltage between the two contacts cannot break down the space between the electrodes. This procedure can be accomplished by: Lengthening of the gap, High pressure, Cooling, and Blast effect.

D. Classification of Mechanical Circuit Breakers

Nowadays, highly protected and available systems are widely demanded, especially with the proliferation of distribution and generation into the power system. There are various types of mechanical circuit breakers that can help in protecting electrical systems[12][22][25][29]. Circuit breakers can be classified into different types. The most common one is based on the medium used for the arc extinction. Depending on the interrupting media, there are different kinds of circuit breakers: Oil Circuit Breakers (Bulk oil circuit breakers, Self-blast oil circuit breakers, Plain explosion pot, Cross jet explosion pot, and Self-compensated explosion pot), Air Blast Circuit Breakers, Sulfur Hexafluoride Circuit Breakers, and Vacuum Circuit breakers.

E. MCB Trip Curve Characteristics

Circuit breakers are used as protective devices in order to provide the safety for the power system. When an over-current occurs, the contacts of the circuit breakers separate in order to turn off the system and interrupt the current. The tripping characteristics of molded case circuit breakers can be represented by a characteristic tripping curve that plots tripping time versus current level[5][36][26][28]. The curve shows the amount of time required for a circuit breaker to trip at a given over-current level, this band bound between the minimum and maximum value is called the total clearing time and which is the sum of the circuit breaker sensing time, unlatching time, mechanical operating time and arcing time. If the current exceeds 125% of the circuit breaker rating at an ambient of 40°C, the circuit breaker will automatically open. Thermal-magnetic circuit breaker trip curve is shown in the Figure 3 below [5][36][26][28]. The thermal tripping response is shown in the upper left portion of the trip curve and which is occurring when a Bimetal conductor in the breaker responds to heat associated with the over-current, and this case occur on the low fault current levels, up to the magnetic tripping level. The appearing of this case will cause the Bimetal conductor to deflect, and mechanically causing the circuit breaker to trip and open the circuit. The larger the overload, the faster the breaker will operate to clear the circuit [5][36][26][28]. The Magnetic Tripping response is shown in the lower right portion of the trip curve and which is occurring when over-currents operate an integral magnetic armature which de-latches the mechanism. Magnetic tripping occurs with no intentional time delay. The adjustment of the circuit breaker in the case of the magnetic response sets the limits of the magnetic trip mechanism, which simultaneously adjust all poles of the two or three pole breaker to the same magnetic trip level. [5][36][26][28]

F. Disadvantages of MCB

In order to detect the overload current or a short circuit, the mechanical circuit breaker is used for this purpose. The time
taken to open the mechanical switch will cause the occurring of
the arc. As a result, the turning off of the switch  will take at least
100 millisecond. Furthermore, the mechanical circuit breaker has
a maximum short circuit current rating.

This current limit forces the designer to limit the short circuit
time of the grid. In addition to that, the peak current in the
mechanical circuit breaker cannot be influenced, which lead to
all the network component to withstand the peak current during
the switching period.

III. SOLID STATE CIRCUIT BREAKERS

A. Introduction

In order to achieve the safety, high availability, and high power
quality of the system when a short circuit or an over-load occurs,
SSCBs have been proposed to keep the system limitations in a
lower distribution level. The SSCB [30][31][35] is a circuit
breaker with solid state devices connected in the circuit, in order
to protect the power system components abnormal operating
condition[14][21][23][28]. The SSCB is a new technology that
can be used to implement various functions and to offer several
advantages as:
- Limiting the fault current
- For different voltage and current levels, stacking the
appropriate module numbers to perform the appropriate
adoption[12]
- If any problem happened to one of the modules in the SSCB,
the broken one can be replaced by a spare module, rather
than replacing the whole circuit breaker in the complete
switch. Therefore, the maintenance and testing of the circuit
will be simplified with less time wasting[12]
- SSCB is a device with no arcing and switch bounce[12]
- SSCB offers a higher reliability than MCB [12]
[5][36][26][28]
- SSCB can switch in a range of microseconds, as opposed to
millisecond for the mechanical circuit breakers[12]
- For a lower voltage level, the individual modules used are
small that will make the design of SSCB more compact[12]

B. Semiconductor Devices Used for SSCB

Three different semiconductor devices can be used in the design
of SSCBs, namely:
- Insulated Gate Bipolar Transistor (IGBT),
- Gate Commutated turn-off Thyristor (GCT),
- Gate-Turn-Off Thyristor (GTO),

The switching losses of these devices can be considered as a
minor issue in the application of the SSCB. However, the
behavior of the SSCB during the conduction and the generated
losses have an essential impact on the losses [22][24][29][32].
The on-state losses of IGBT are significantly higher than the
losses of a thyristor-based semiconductor. However, the IGBT
has the advantage of automatically limiting the current to a
certain value. In contrast, the current in a thyristor-based device
is not limited, while the turn-off capability is restricted[22][24][29][32]. Bidirectional blocking voltage
capability and bidirectional current conduction paths are needed
for the AC SSCB. Figure 4 shows different types of AC
switches[2][14][20][22]. In order to select one of AC switches,
different aspects and topologies should be considered. So, the
factors to be considered are:
- Withstanding voltage,
- Load current capability,
- Turn off behavior,
- Conduction losses,
- Availability,
- Cost and complexity.

In the development of SSCB, minimizing the conduction losses
during normal operation is needed due to their significant effect
on the efficiency [2][14][20][22]. The conduction losses strongly
depend on the switch structure. The power losses for different
configuration is differing. Since IGBT has been used in the
hardware implementation then only figure 4C, E and F should be
considered. For the design simplicity and reliability, having less
controllable devices with high power losses is preferred rather
than using more controllable devices with less power losses
[21][24][28][32]. The bridge circuit, shown in Figure 4F,
consists of only one IGBT or MOS transistor. Hence, there is
a need for only one gate control to arrange a diode bridge. The
diode-bridge arrangement has 5 semiconductor devices in
which, every two diodes with the IGBT is used to build up
a conducting path for the current. Using one IGBT adds more
simplicity to the SSCB, reduces material cost, and increases the reliability [2][14][20][22].

D. Electronic Circuit Breaker Trip Characteristics

The electronic trip circuit breaker can be adjusted by varying the setting of the available trip unit function. Figure 5 shows the trip curve for the electronic circuit breaker with a various discrete segments[2][14][20][22].

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IV. SIMULATION

A. Simulation of the SSCB

To understand the basic operation of the proposed SSCB, a single phase equivalent circuit which is shown in the figure 6 below has been used where the grid is represented by a voltage source and a line inductance, and the load represented by a pure resistance.

B. Simulation for SSCB using the curve fitting method

The basic single phase equivalent circuit is represented in the MATLAB/Simulink as shown in the figure 7 below in order to determine the behavior of the current before and after the interruption where a real data of time-current curve has been used using the curve fitting method in order to interrupt the circuit[21][24][28][33]. The table below shows the parameter used in order to build the single phase equivalent circuit.

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated current</td>
<td>30</td>
<td>A RMS</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>220</td>
<td>V</td>
</tr>
<tr>
<td>Resistance</td>
<td>10</td>
<td>Ω</td>
</tr>
<tr>
<td>Inductance</td>
<td>1e-3</td>
<td>H</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>80</td>
<td>A RMS</td>
</tr>
</tbody>
</table>

The exponential equation of the tripping time is represented as \( t_{\text{tripping}} = (79.4 * (I -24.5)^{1.27}) \) and it is used in order to interrupt the circuit after the appearing of the fault. Two ases will be simulated in this section.

Case 1: Temporary faults: are faults which do not damage the system permanently and allow the circuit to be safely re-energized after a short period of time.

A typical example would be an insulator flashover following a lightning strike, which would be successfully cleared on the
opening of the circuit breaker, which could then be automatically released. Figure 8 below shows the response of the system when the first fault happened. It is clearly shown that the high current which is almost 1700 A appearing at 0.1 Sec is tremendously higher comparing to the rated current.

Case 2: Permanent fault: It is due to the result of permanent damage to the insulation. In this case, the equipment has to be repaired and reclosing must not be entertained. Figure 9 shows the response of the system when the fault happened. It is clearly shown that the fault current appears firstly at 0.1 seconds which lead to turn off the system for only one cycle (0.02 second) in order to interrupt the fault. Open the system again after that interruption shows that the fault still existing even after 0.22 seconds which lead to completely turn off the system.

C. Simulation of SSCB using Look Up Table Method

The basic single phase equivalent circuit is represented in the Matlab Simulink in order to determine the behavior of the current before and after the interruption where a real data of time-current curve has been used in a table in order to interrupt the circuit.

Simulation results for lookup table method

After running the MATLAB/simulation program, different graphs of the current after the appearing of the fault has been taking as shown in the figures below where different values of the fault resistances R=0.9 ohms, R=0.4 ohms and R=0.001 ohm have been used respectively as shown in the figure 10, 11, and 12.

V. HARDWARE WORK

A. Components used for the SSCB implementation

The employed DSP is the ezdsp TMS320F28335. The DSP used has up to 18 digital output pins where one of the them is used to control the IGBT switch.

![Image](image1.png)

Figure 10. The Current Waveform With A Fault Resistance Of 0.9 Ohm

![Image](image2.png)

Figure 11. The Current Waveform With A Fault Resistance Of 0.4 Ohm

![Image](image3.png)

Figure 12. The Current Waveform With A Fault Resistance Of 0.001 Ohm

![Diagram](image4.png)

Figure 13. Diagram For The Connection For Testing The IGBT

Table 2. Rating Current And Voltage Of Components

<table>
<thead>
<tr>
<th>Rating</th>
<th>Current (Amps)</th>
<th>Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT</td>
<td>60</td>
<td>1000</td>
</tr>
<tr>
<td>Diode</td>
<td>60</td>
<td>1000</td>
</tr>
<tr>
<td>Current transducer</td>
<td>(50-70)</td>
<td>-</td>
</tr>
<tr>
<td>Gate driver circuit</td>
<td>-</td>
<td>5</td>
</tr>
</tbody>
</table>
VI. HARDWARE RESULTS

A. Testing the SSCB

Because of the availability and capability of the lab, and for safety issues, all the tests of the SSCB have been done at low voltage levels. Firstly, a single phase supply (240 V rms) is applied to the power resistor with 225 Ω to scale down the current in order to get its value between 1 and 3 A. The output of current transducer will be connected to ADC pin on the DSP. ADC will see the voltage as a number of counts, where 3 volts is corresponding to 4095 counts. At this stage, DSP will send the value of the voltage as the number of counts to the MATLAB/Simulink file and transform it to its original value of the instantaneous current. After that, the value of the instantaneous current will be compared with the comparator, if it is greater than 1 Amps, the program will see the look up table and check the fault current value and it is corresponding interrupting time. As an illustration, if the output voltage of the current transducer is 2.5 volts, in this case ADC will read the voltage as 3412 counts \((\frac{2.5 \times 4095}{3}) = 3412\). Accordingly, if the fault current is 2.2 Amps the program will look for the lookup table that is already constructing inside the MATLAB/Simulink file and see the corresponding tripping time for 2.2 Amps fault current and it is corresponding tripping time which we set it in the lookup table to be 10 Sec. In this case, the program will wait for 10 Sec and then send a zero order to the bidirectional switch to trip the circuit and stop the fault. The MATLAB/Simulink program that it has been used in order to trip the circuit when a fault occur is shown in the figure 14 below.

![Figure 14. MATLAB/Simulink Program For The Fault Tripping](image)

The figure 15 below shows hardware prototype of the SSCB.

![Figure 15. Testing Circuit](image)

B. Experimental results

Long-time Ampere Rating and Delay

The figure 16 below shows the response of the current and voltage signal before and after the occurring of the fault. Before the fault occur the current was 0.502 A, after making the short circuit test between one of the two resistors which are connected in series (420 ohm), the current rise suddenly to reach a value of 10.5A.

![Figure 16. Detecting Of The 1.05 A Fault Current](image)

Short-time Pickup and Delay

The figure 17 below shows the response of the current and voltage signal before and after the occurring of the fault. Before the fault occur the current was 0.73 A, after making the short circuit test between one of the two resistors which are connected in series (300 ohm), the current rise suddenly to reach a value of 1.46 A.
Instantaneous Pickup

Figure 18 shows the response of the current and voltage signal before and after the occurring of the fault. Before the fault occurred, the current was 1.465 A, after making the short circuit test between one of the two resistors which are connected in series (150 ohm), the current rises suddenly to reach a value of 2.93 A.

The figure 19 below shows the response of the current when it has been tripped at its maximum value.

VII. CONCLUSION

Solid-state Circuit Breakers offer several features compared to mechanical circuit breakers such as nearly unlimited short circuit capacity by current limitation, programmable trip time curve, programmable rated current, controlling facilities and monitoring functions for current and voltage. The objective of this paper is to study and implement a smart prototype of SSCB for smart grids. The presented SSCB is controlled through the current/time characteristics of that used in the conventional mechanical circuit breakers in addition to limit the high fault current levels (fault current limiter) especially with the proliferation of the distributed generation and the associated fault current level increase. In this paper, the principle of operation of the mechanical circuit breaker (MCB) and their classifications are introduced, and switches used in the design of SSCBs are presented. Simulation of SSCB is carried out to study its feasibility and performance in the case of various operating conditions. Then, a hardware prototype of SSCB using IGBTs devices is constructed and tested to elucidate the proposed concept.

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