Dc Micro Grid Protection with the Z-Source Breaker

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Abstract - Many components of a modern micro grid operate using a dc interface including solar panels, fuel cells, and battery energy storage. For this reason, a dc micro grid has been suggested and utilized in some power systems. This paper starts with consideration of the dc micro grid with protection placed on each component. With the absence of a zero-crossing in the current waveform, the dc breaker faces a unique challenge in that there is no natural method of extinguishing an arc that occurs during breaker operation. This is handled in practice by using over-sized ac breakers or using a solid-state breaker. A recently introduced z-source breaker is a unique form of the solid-state breaker that automatically responds to system faults. It has the ability to clear the fault within microseconds. Furthermore, the source will not experience the fault current. The theory behind the z-source breaker is reviewed. Design methods and dc micro grid operation examples of the z-source breaker are shown.

Index Terms -- Power grid, smart grids, power system faults, circuit breakers, thyristor circuits.

I. INTRODUCTION

In recent years, micro grids have become exceptionally popular. Micro grids are seen as a bridge between the traditional grid with central generation and the future grid with distributed, renewable, generation. A micro grid area in a power system places distributed generation close to the load. With proper control, the micro grid can operate with minimal power from the utility grid; thus maximizing the use of renewable energy.

Some researchers suggest a dc system for the micro grid [1-4]. As an example, consider the conceptual micro grid shown in Figure 1. A number of non-traditional sources such as fuel cells, wind, and solar are incorporated along with advanced energy storage represented by the ultracapacitor. These energy sources rely on power conversion to interface to the grid. However, most of these sources initially produce dc voltages. Therefore, there may be some advantages in utilizing dc for the micro grid. Synchronization for bringing new generation on line is not required. Frequency regulation is not a concern. Power conversion for dc generation is simplified.

Although the power conversion is simplified in the dc micro grid, protection remains an outstanding concern due to the lack of a zero crossing in the current. In ac systems, this zero crossing extinguishes the arc produced when a breaker is opened. For dc systems, one option for protection is to utilize over-sized ac breakers. Another option is a hybrid breaker with a main mechanical switch augmented by solid-state devices [5-8]. A third option is a purely solid-state breaker [9-12]. These tend to have higher losses, but fast response. This paper suggests the use of a new type of solid-state breaker, referred to as the "z-source" breaker. The z-source breaker has the advantage of automatically switching off in response to a local fault. Therefore, these may be placed at the interface to each source and load as indicated by the "Z" blocks in Figure 1. With this structure, if a fault occurs in one
of the sources or loads, it will be automatically disconnected from the micro grid.

This paper describes the z-source dc circuit breaker. Simulation examples on various dc micro grids are presented.

II. THE Z-SOURCE DC CIRCUIT BREAKER AND OPERATION

This project begins with the introduction of a novel dc circuit breaker which is shown in Figure 2. Therein, the z-source breaker consists of an SCR, a crossed L-C connection, diodes, and resistors. The system load is represented by the R-C circuit consisting of \( R \) and \( C \). A fault is depicted by the conductance \( G_f \). The z-source L-C connection was initially suggested as a novel type of inverter input circuit [13-16] that could operate in boost, as well as the standard buck, mode. The reason for this is that the z-source allows another state wherein the inverter can short-circuit its dc bus. Herein, this feature is adopted for fault handling in dc power systems. When the fault occurs in this system, there is no direct short of the z-source capacitor voltages, because of the inductors in the z-source circuit. The breaker components act together to quickly mitigate faults in a dc system. When a fault occurs at the output of a z-source breaker, current sources into the fault from the downstream system capacitance \( C \) as well as from the z-source capacitances as shown by the fault conduction path in Figure 2. The full set of waveforms during the fault are shown in Figure 3. In this system, the source voltage \( v_s \) is set to 6kV and the load is set for 6MW (\( R = 6\Omega \)). The system is operating in the steady-state and the fault conductance is ramped from zero to 50S. The operation of the z-source circuit can be understood by considering the current path shown in Figure 2. A portion of the fault current will come from the z-source breaker capacitances. In the transient state, the inductor keeps the current \( i_L \) constant as seen in Figure 3. The conduction path is then through the z-source capacitors and back to the source as shown in Figure 2. Therefore, the capacitor current \( i_C \) is seen in Figure 3 to increase until it matches \( i_L \). At this point, \( i_{SCR} \) will go to zero causing the SCR to commutate off. A simple circuit can then detect that a fault has occurred and remove the gate voltage from the SCR. After the SCR switches off, the z-source components are configured as two series L-C branches connected to the load and fault. These circuits start a resonance where they are supplying the fault, but since the source has been disconnected and the fault impedance is low, the output voltage collapses to zero. By KVL, with the output voltage at zero, \( v_L \) must be equal to \( v_C \). In Figure 3, it can be seen that the inductor and capacitor voltages become equal when the output voltage goes to zero. Also, by KVL, it can be shown that when these voltages reach half of the source voltage \( v_s \), the SCR will become forward biased. Therefore, the time when \( v_{SCR} \) is positive is the amount of time available for the control circuit to remove the gate pulse and the SCR to undergo its reverse recovery transient. The resonance continues until the inductor voltage attempts to go negative. At this point, the diode will turn on. The current in the capacitor will switch off and the current will continue in the inductor/diode/resistor loop until it decays to zero. It can also be shown by KVL that since the inductor voltage does not go negative, the SCR voltage will not go above the source voltage. Figure 3 also shows the source current \( i_{SCR} \) immediately going to zero when the fault occurs, as desired. After the SCR goes off, the fault has successfully been isolated.

III. Z-SOURCE BREAKER FAULT TRANSIENT

The first part of the analysis involves determining the z-source impedance values required, relative to the system parameters, to cause the breaker to switch off. Neglecting the SCR and inductor resistance voltage drops, the steady-state SCR current is

\[
I_{SCR} = \frac{v_f}{R_f} \quad (1)
\]
The initial transient is based on the fault conductance. For the purpose of this analysis, the conductance is assumed to ramp from zero to a final value with a ramp rate of

\[ K = \frac{1}{dt \cdot R_p} \]  

(2)

where \( dt \) is the time for the conductance to ramp to its final value which is the reciprocal of \( R_p \). For the first part of the analysis, it is assumed that the inductor current remains constant. Then, the transient fault current takes a path supplied by the capacitances as displayed in Figure 2. Since the fault current is related to the output voltage by

\[ i_f = G_j v_o = K v_o t \]  

(3)

The fault current is being supplied from two capacitances; one being the load and one being the series combination of the z-source capacitors. Considering these impedances and the current division rule, the capacitor currents due to the fault are

\[ i_c = \left( \frac{C}{C+2C_j} \right) i_f = C_s i_f \]  

(4)

\[ i_{cl} = \left( \frac{2C_j}{C+2C_j} \right) i_f = C_h i_f \]  

(5)

Equations (4-5) neglect the effect of source inductance, but provide accurate results. Calculating the current being supplied by the load capacitor from (1) and (3), the transient output voltage can be computed as a change from its steady-state value as

\[ v_o = v_s \left( 1 - \frac{C_s K}{2C_j} t^2 \right) \]  

(6)

The fault current can then be expressed from (3) and (6) as

\[ i_f = v_s K t - \frac{v_s C_s K^2}{2C_j} t^3 \]  

(7)

The transient current through the z-source capacitor is then computed from (4) and (7) as

\[ i_c = v_s C_j K t - \frac{v_s C_s C_g K^2}{2C_j} t^3 \]  

(8)

Although the change in inductor current is slight, it can be computed by first determining the inductor voltage using (6) to be

\[ v_L = \frac{v_s C_s K}{4C_j} t^2 \]  

(9)

Considering the steady-state value, the transient inductor current can be determined as

\[ i_L = I_{SCR} + \frac{v_s C_s K}{12LC_j} t^3 \]  

(10)

By KCL, the SCR current during the fault can now be determined as

\[ i_{SCR} = I_{SCR} - v_s C_s K t + \frac{v_s C_s K}{12LC_j} (6LC_s K + 1) t^3 \]  

(11)

Under the appropriate conditions, the SCR current will go to zero and shut off. For these cases, the minimum SCR current will be less than or equal to zero. Taking the derivative of (11) and setting it to zero yields the time at which the current reaches a minimum which is

\[ t_{min} = \frac{\sqrt{2CL}}{\sqrt{6C_s LK + 1}} \]  

(12)

The minimum current can be computed by substituting (12) into (11) for time. It should be noted that (11-12) are valid during the transient state while the conductance is ramping up \((t \leq \frac{dt}{d})\). By knowing the downstream system load capacitance, (11) can be used to determine the capacitance required in the z-source breaker so that the circuit switches off during a fault. Figure 4 shows the minimum amount of z-source capacitance required for a specific amount of load capacitance. As can be seen, the relationship appears as a straight line on a log scale. According to (11), the current is a function of the conductance rate of change \( K \) of which three values are shown in Figure 4. In this example, the source voltage was \( v_s = 6 \text{kV} \), the load resistance was \( R_L = 6 \Omega \), the inductance was \( L = 200 \mu \text{H} \). According to (11), the inductance plays a small role in the shape of the current. To illustrate this point, the inductance was changed to \( L = 100 \mu \text{H} \) for the very top trace in Figure 4. Only a slight change in required z-source capacitance is seen.
For faster ramping fault conductances, the capacitance required for the z-source circuit to switch off is smaller. For a step change in fault, the fault current can be set to the output voltage times the fault conductance. Equation (4) can be used to reflect this current back through the z-source circuit. Solving the equation yields

\[ C_S = \frac{I_{SCR}}{v_G} \]  

(13)

Using (4) a minimum value for \( C \) can be calculated as

\[ C_{min} = \frac{2C_I I_{SCR}}{v_G G_f - I_{SCR}} \]  

(14)

After the SCR switches off, the z-source circuit undergoes a resonance which is discussed in the next section.

IV. Z-SOURCE BREAKER RESONANCE

After the z-source breaker interrupts a fault, the SCR must go through its reverse recovery process. The resonance of the L-C circuit allows a time for this to occur. Sufficient sizing of the inductor and capacitor components must be carried out to ensure that the SCR has time to completely switch off before the resonance results in a forward bias of the SCR. After the SCR current goes to zero, the output voltage collapses in a matter of microseconds; the exact time depending on the amount of source inductance. With the output voltage at zero, the inductor voltage equals the capacitor voltage \( v_L = v_C \). As can be seen from Figure 2, with \( v_o = 0 \), the SCR voltage is

\[ v_{SCR} = v_s - 2v_C \]  

(15)

This voltage will become positive when the capacitors discharge to half of the source voltage. During resonance, the capacitor voltages can be expressed as

\[ v_c = v_o \cos(\omega_o t) \]  

(16)

where the resonance frequency is

\[ \omega_o = \frac{1}{\sqrt{LC}} \]  

(17)

By setting the capacitor voltage to one-half the source voltage, the resonance time can be computed as

\[ t_{res} = \frac{\pi}{4 \omega_o} \]  

(18)

Since the main SCR commutation time is neglected, (18) is approximate, but has been shown to be accurate when compared to detailed simulation results. Consider the 6kV 6MW system described above with a 10 m\( \Omega \) stepped fault. Equation (18), was used to characterize the resonance time. Figure 5 shows this time as a function of the inductance and capacitance of the breaker.

Using a plot such as Figure 5, and considering the turn-off time of a specific SCR, the minimum inductance and capacitance can be determined. The minimum capacitance should also be verified with Figure 4 to ensure that the SCR will switch off.

V. PHYSICAL COMPONENT SIZING

The sections above provide a guideline for selecting the z-source breaker inductance and capacitance. The physical size of the components will now be considered. First, consider a 6MW 6kV system with a 20 m\( \Omega \) fault ramped at a rate of \( K = 5 \times 10^6 \Omega^{-1} \text{s} \). In this example, the capacitance was first selected to be \( C = 125 \mu\text{F} \) based on available sizes. The
inductance was selected to be $L = 200 \mu H$ using Figure 5 so that the commutation time will be over $100 \mu s$. In general, it is advisable to avoid inductor and capacitor selections where the inductance (in H) is considerably different than the capacitance (in F) in order to maintain the same commutation time and minimize the component size. Also, designs with a excessive amount of capacitance will lead to a higher peak resonant current. The capacitance is also above the minimum value of approximately $40 \mu F$ predicted using Figure 4. The system simulation during the fault transient is that shown in Figure 3.

As can be seen, the inductor current rises from the pre-fault value of 1kA to a peak value during the resonance of nearly 4.5kA. After the inductor and capacitor current depart, the inductor current circulates in the diode and decays to zero in about 5ms (with a 100 ohm resistor). Because of this large ratio of peak to nominal inductor current, an air-core inductor is recommended. The inductance of a loop of wire in air is

$$L = N^2 R \mu_0 \left[ \ln \left( \frac{8R}{a} \right) - 2 \right]$$

(19)

where $N$ is the number of turns, $R$ is the loop radius in meters, and $a$ is the radius of the wire in meters. It can be determined for the desired value of inductance of $L = 200 \mu H$, 20 turns of wire with a 2.5cm. diameter in a 30cm. loop is sufficient. The 2.5cm. diameter is also the amount necessary to carry the nominal current of 1kA. Physically, the inductor would be a cylinder of 30cm. diameter and approximately 30cm. in length.

For the capacitance, there are a number of options available from manufacturers. Based on series combination of off-the-shelf capacitors, a capacitance of $125 \mu F$ at 6kV with a peak current of 4.5kA is estimated to have dimensions of 21cm. by 42cm. by 19cm.

VI. LABORATORY VALIDATION

In order to test the concepts presented herein, a low-power z-source breaker was assembled in the laboratory. Figure 6 shows the constructed z-source breaker. The SCR is seen mounted on a heat sink at the left of the board. The inductors (round) and capacitors (square) are the larger components next to the SCR. The diodes are the very small components next to the inductors. The resistors in series with the diodes (as seen in Figure 1) were not included since the inductors have enough resistance $r_L$ to dampen the inductor currents.

![Z-source breaker hardware](image)

The specific ratings and parameters are listed in Table I. The limitation of z-source breaker rated voltage $V_z$ and current $I_z$ is based on the ratings of the inductors and capacitors.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_z$</td>
<td>250 V</td>
</tr>
<tr>
<td>$I_z$</td>
<td>10 A</td>
</tr>
<tr>
<td>$V_{RMS}$</td>
<td>400 V</td>
</tr>
<tr>
<td>$I_{RMS}$</td>
<td>40 A</td>
</tr>
<tr>
<td>$C$</td>
<td>50 \mu F</td>
</tr>
<tr>
<td>$L$</td>
<td>820 \mu H</td>
</tr>
<tr>
<td>$r_L$</td>
<td>154 m\Omega</td>
</tr>
</tbody>
</table>

For the first test the z-source breaker is operating in a system with a source voltage of $v_s = 120 V$ and is supplying lamp and motor loads totaling 660W when a direct short is created across the load bus. Figure 7 shows the z-source breaker response. As can be seen, the source current $i_{SCR}$ immediately goes to zero. The response is similar to the simulated response in Figure 3 with the addition of a reverse recovery transient. The behavior of the SCR voltage $v_{SCR}$ is similar to that predicted by the simulation. In this case, the load did not contain any capacitance so the output voltage drops suddenly in response to the fault. The SCR voltage then steps to the source voltage and remains positive as the inductor and capacitor resonate with the fault. As can be seen, the SCR voltage remains positive for over $100 \mu s$ which is well above the SCR turn-off time shown in Table I. Therefore, the SCR remains off as long as the resonance occurs and its voltage settles to $-v_s$. Initially the inductor current $i_L$ is supplying the load and the capacitor current $i_C$ is zero. When the fault is applied, the capacitor current rises and exceeds the inductor current during the reverse recovery mode. It then matches the inductor current during resonance until the SCR voltage reaches $-v_s$. At this point, the z-source diodes conduct. The inductor current departs from the capacitor current and circulates in the diode. As can be seen, the inductor resistance will dampen the inductor current and it will return to zero in approximately 1ms. The capacitor current is seen to go to zero and exhibits an additional ringing which is not seen in the simulation. However, simulation studies verify that this is due
to an additional $4 \mu H$ of inductance in series with the capacitor which comes about from the current sensor.

![Figure 7. Z-source breaker laboratory measurements.](image)

VII. DC MICRO GRID ILLUSTRATIONS

There are numerous ways in which the z-source breaker can protect the dc micro grid. Figure 8 shows a series connection. In these systems, entire sections are supplied from a single source through "downstream" breakers. In this example, the generator G supplies four load centers through breakers Z1 to Z4 as shown. A simulation of this system was created with a 6kV dc link where each load had a rated power of 6MW and the generator/rectifier was modeled using an average-value technique [17]. Faults were placed at various locations and a set of studies were carried out.

![Figure 8. Series z-source breaker connection.](image)

Figure 9 shows the case where the fault is placed on the specific load as indicated in Figure 8. Therein, the currents $i_{z1}$ through $i_{z4}$ represent the current in z-source breakers Z1 through Z4 respectively. It is clear from the breaker currents that Z3 has activated removing the two loads downstream. Therefore, $i_{z1}$ goes to half its rated value.

![Figure 9. Series z-source breaker operation.](image)

Figure 10 shows an arrangement that might be more common in smaller, less elaborate dc micro grids. Essentially, each source and load is protected with a corresponding breaker and could be viewed as a shunt topology.

![Figure 10. Shunt z-source breaker connection.](image)

Figure 11 shows the simulation results of the shunt dc micro grid with the fault on the center load as indicated in Figure 10. From the z-source breaker currents, it is clear that one-third of the load has shed and in particular, the faulty load is removed by breaker Z3 without disturbing the rest of the system.

![Figure 11. Shunt z-source breaker operation.](image)
Figure 12 shows a dc micro grid with two sources supplying two loads. For this study, the z-source breaker has been modified to be a bi-directional version. Although it is beyond the scope of this paper, the bi-directional z-source breaker can be constructed by placing a diode in anti-series to the SCR and placing the same semiconductor arrangement on the opposite side of the z-source L-C arrangement.

In this last example, a fault is created at the output of one of the generating units as illustrated in Figure 12. The z-source breaker currents are shown in Figure 13. Initially, both generators are sharing the load. After the fault, one generator is tripped off by breaker Z2; transferring the full load to the other generator. A slight disturbance is seen in the load currents, but the supply to the loads is continued.

Figure 13. Operation with source fault.

VIII. CONCLUSION

The micro grid has gained considerable attention in recent years; as it is seen as a method of incorporating renewable energy into the traditional power system grid. When creating a micro grid, a dc system is a reasonable option, as many energy sources are dc and require only a straightforward voltage conversion. One limitation of the dc system is the availability of standard types of protection. This paper describes a recently developed z-source dc circuit breaker that is applicable to the dc micro grid. As described, it has the capability to automatically respond to faults and therefore quickly isolate the faulted components. Simulation and laboratory measurements demonstrate that the z-source breaker operates in microseconds. This technology is then studied using a number of example dc micro grids. System simulation shows effective fault isolation and continued operation using the z-source breaker.

REFERENCES


