Abstract—We present a new approach to protect a multi-branch medium-voltage DC bus from ground faults. Behavior analysis of a DC distribution scheme shows that it is possible to quickly de-energize the DC bus by controlling the main converter, open a contactor to remove the faulted line, then re-energize the system. This strategy reduces the out-of-service time and avoids the use of mechanical circuit breakers and their arc-eliminating equipments. The fast response time allows unaffected loads to ride through the process with minimal local energy storage. Our research shows that it is possible to de-energize, reconfigure, and re-energize a typical industrial DC bus 10-20 times faster than methods traditionally applied in AC circuits, and that only 470 µFarad of bus capacitance is needed for unaffected circuits to ride-through the process uninterrupted.

I. INTRODUCTION

DC power distribution at the low voltage level is becoming common for data centers. Less common are DC distribution systems at the medium voltage level, and these are partially hindered by lack of appropriate circuit protection strategies and equipment [1]-[3]. Our purpose in this paper is to show how electronic power converters can be controlled to effect the circuit protection strategy so that traditional circuit protection elements are not needed. This is particularly important since traditional AC circuit breaker mechanisms, which rely on arc extinction at the period zero crossings of current in order to open the circuit, are inadequate to interrupt direct currents. Indeed, providing of an arc-eliminating equipment is necessary for this kind of devices. This choice is more complex and requires more space [4]. Therefore, many techniques have been proposed in the literature to induce an oscillating current zero to interrupt the current, and to employing mechanical CBs or expensive solid state circuit breakers, the discussed solution allows the re-energizing of a DC bus after a ground fault in 10-20 times faster than the trip time of circuit breakers. A protection system acting within a few milliseconds allows the isolation of the faulty branch and the re-energizing of the entire bus such that the healthy branches are not aware that the main bus has been brought down and reconfigured. Figure 1 shows the scheme that has been explored in simulations. A main DC/DC converter supplies power to the multi-branch DC distribution bus. When a ground fault happens, while the faulty branch absorbs a large amount of energy, the healthy lines are isolated by the input diode. Therefore, healthy converters on healthy lines are able to supply power to each load for a time depending on the size of the converter input capacitor. The converter control, the output capacitor (C_{OUT}) and its protection, input diodes, downstream input capacitors and branch switches are involved in this process. The switches; SW1, SW2, and SW3; are contactors, which means that when they are closed the circuit operates, but they can be opened to isolate faulty branches. In the analysis, we assume that they are not capable of interrupting the fault current, and they do not need to.

In this paper a new approach is presented that consists in a controlled power sequencing. As opposed to inducing an oscillating current zero to interrupt the current, and to employing mechanical CBs or expensive solid state circuit breakers, the discussed solution allows the re-energizing of a DC bus after a ground fault in 10-20 times faster than the trip time of circuit breakers. A protection system acting within a few milliseconds allows the isolation of the faulty branch and the re-energizing of the entire bus such that the healthy branches are not aware that the main bus has been brought down and reconfigured. Figure 1 shows the scheme that has been explored in simulations. A main DC/DC converter supplies power to the multi-branch DC distribution bus. When a ground fault happens, while the faulty branch absorbs a large amount of energy, the healthy lines are isolated by the input diode. Therefore, healthy converters on healthy lines are able to supply power to each load for a time depending on the size of the converter input capacitor. The converter control, the output capacitor (C_{OUT}) and its protection, input diodes, downstream input capacitors and branch switches are involved in this process. The switches; SW1, SW2, and SW3; are contactors, which means that when they are closed the circuit operates, but they can be opened to isolate faulty branches. In the analysis, we assume that they are not capable of interrupting the fault current, and they do not need to.

The challenge of this paper is to study the feasibility of a control process which minimizes the fault current magnitude...
II. FAULT DYNAMICS ANALYSIS

When a ground fault happens (t=0) on a branch of the DC bus, the fault dynamics is divided into three main parts.

A. Current rising. The first dynamic is that the rising of the current can be stopped by shutting off the main converter or by controlling its valves, e.g. when the current reaches three times the rated circuit current.

B. De-energizing process. Once the main converter is shut off, the output inductance and capacitor discharge their energy on the faulty bus with a time constant depending on the fault distance.

C. Re-energizing process. Once the current is definitely brought to zero, the switch SW3 can isolate the faulty branch, and the main bus has to re-energize the entire DC bus to come back to the operation state.

III. DE-ENERGIZING PROCESS ANALYSIS

The new converter generations are able to limit the current requested from a DC bus and to instantaneously interrupt the current flow from the upstream to the downstream side of the converter. They cannot stop the output inductance and the output capacitor from supplying a ground fault on one of the branches. However, the introduction of appropriate protections allows (i) avoidance of damage to the converter’s components and (ii) limiting of the ground fault current. We introduced a freewheeling diode to prevent voltage reversal on the capacitor. An Emitter Turn-Off (ETO) thyristor-based solid state device can be used to protect the output capacitor of the main converter as presented in references [5][7], but we can prevent the use of this expensive device by using our new approach. We did an analytical analysis of the discharging process by investigating the dominant transient after the main converter valve was turned off. In this case, we have a RL transient composed by the main converter output inductance, the DC bus inductance and resistance, and the fault resistance. With the worst conditions, i.e. with a fault distance of 100 meters, the results show a current transient trend of first order with a time constant of:

\[ \tau = \frac{L}{R} = 3.126 \text{ms} \]

The time to reach the complete discharge is about 14 ms.

### Figure 3 Analytical analysis circuit

In order to have a better model accuracy, we did a transient analysis through Simulink® simulations, by inserting a π distributed line between the main converter and the ground fault with the following values:

<table>
<thead>
<tr>
<th>Table I. π DISTRIBUTED LINE</th>
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<tr>
<td>R [mOhm/m]</td>
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<td>0.193</td>
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In Figures 4, the de-energizing transient is shown.

The DC bus length variation, which is the distance from converter to fault, and the maximum current threshold are parameters we have considered.

The possibility of shutting off the main converter when the line current reaches a limiting value allows a bus fault current which is 10-100 times smaller than fault currents that would otherwise occur by protecting the system with mechanical circuit breakers. With our solutions, however, the natural bus de-energizing involves a discharge time between 2 and 12 ms based on bus length and intervention threshold values.
The result from the transient analysis of the DC bus discharge is that there is a large dependence between discharge time and the distance of the ground fault from the main converter. Considered distances are from 3 to 100 meters (Figure 5).

The maximum current value at which the main converter is shut off affects the discharge time because the current going through the output inductance is higher and the energy that the DC bus has to dissipate is greater.

\[ W = \int_{t_1}^{t_2} i(t) \, di(t) \]

Looking at the literature, we assume that the current limit is about three times the rated current \([6][8]\). The graph of Figure 6 shows the time to reach the rated current as 50% and 10% of the rated current, respectively.

IV. RE-ENERGIZING THE DC BUS

In order to provide the ride through capability for healthy branches, the time to re-energize the entire bus must be short. For this reason, the bus charging process for different lengths and different voltages on healthy branches’ converter input capacitors has been studied. Figure 7 illustrates the voltage trend graph which shows the most significant re-energizing behavior.

From the study, it emerges that it is possible to re-energize the entire DC bus within 0.8 ms with the worst conditions: 100 meters DC bus length and 50% input capacitor rated voltage. Looking at the whole process (Fig. 2), we can see that the natural de-energizing and re-energizing of a DC bus by turning off the main converter, need an intervention time between 3 and 14 ms under the specified conditions. This result shows that it is possible to protect the DC bus from ground fault with an inexpensive method. That method does not require additional devices, except the controlled main converter and contactors. Analysis shows that the fault elimination time can be 10-20 times shorter than that requested from a DC circuit breaker because the protection system does not have to interrupt the entire fault current as in the case using CBs \([9]\). This solution is cheaper as well.
V. CONTROL SEQUENCE

This study concerns the feasibility of the control process strategy too. This strategy has to answer to the needs to identify the fault and to turn the converter off as soon as possible, when the current rises over a certain threshold.

![Figure 9 System behavior with the Power Sequencing](image)

The control process is based on current control of the main converter and on operation coordination as well. Indeed, we propose the possibility of shortening the de-energizing time by the addition of ordinary solid state switches (i.e. IGBTs) or contactors which are capable of intervening with current value close to the rated current or some rated current percentage (Fig.9). This means that when the fault current in the faulty branch falls under a particular rated current percentage, the switch is able to isolate the faulty branch.

![De-energizing time [ms]](image)

With this kind of operation it is possible to reduce the de-energizing time by about 3 ms for the more critical situations. Figure 10 shows the comparison between our solutions and state of the art. The operation time reduction allows converters in healthy branches to continue supplying their own loads by means of the input capacitor. This buffer function of input capacitors takes part in the protection coordination process.

VI. RIDE THROUGH CAPABILITY

We have also considered the feasibility of the buffer function of the input capacitor of healthy branches. It appears that to supply the loads for about 3 ms, we need a capacitor size between 140 and 470 µFarad with a ESR between 1 and 2.9mOhm. This means that over-sizing of the input capacitor is possible. The amount of energy dissipated into the ESR of the capacitor and the discharge efficiency are expressed as

$$E_{dis} = \int_{0}^{T_{dis}} i(t)^2 \cdot ESR \cdot dt$$

$$\eta = \frac{E_{dis}}{E_{dis} + E_{tot}}$$

The discharge efficiency result is about 0.999-0.9996 for this range of capacitances.

VII. CONCLUSION

This paper shows that the protection of a multi-branch medium voltage DC bus from ground fault can be carried out by controlling the main converter that supplies the main bus. From the transient analysis of the DC system emerges that the de-energizing action carried out from a main converter control is advantageous for two main reasons: low fault currents and short de-energizing time. Moreover, the control strategy and coordination can avoid the loss of power because the system is capable of de-energizing the bus, isolating faulty branches, and re-connecting the entire bus quickly enough that other loads are not aware that a ground fault has happened. The control process development will be presented in a future paper, and the influence of the coordination process on the size of components and control strategy will be analyzed too.

REFERENCES


