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Metrology Requirements of State-of-the-Art Protection Schemes for DC Microgrids

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Abstract

Environmental incentives to combat climate change are providing the motivation to improve the energy efficiency of power distribution systems and integrate state-of-the-art renewable technologies. Examples include wind/PV resources, energy storage systems and electric vehicles integrated via efficient power electronic converters (PEC). Subsequently, DC microgrids (MGs) and distribution systems are receiving considerable attention in the literature because they offer a simple, yet flexible, interface between these modern resources and consumers. However, many technical challenges relating to the design and standardization of DC protection devices still exist that must be overcome prior to widespread adoption. For example, many protection schemes tailored for DC MGs have been proposed but few of them have considered the metrology requirements for practical implementation. This paper will first review the key features of DC-side fault transients simulated on a DC MG model in MATLAB/Simulink, and analyse the disruptive impact on PEC components. Secondly, a review of newly published DC protection schemes is performed. These protection schemes are classified by their fundamental operating principles and mathematically-derived metrology requirements are given.

1 Introduction

Recent advancements in power electronic converter technologies have resulted in the development of high-efficiency AC-DC conversion, enabling high-voltage DC (HVDC) power transmission[1] and low-voltage DC (LVDC) distribution systems[2]. Whilst HVDC has already been widely installed in many countries, the commercial rollout of multi-terminal DC distribution systems still requires further research, development and standardisation before being extensively utilised.

DC microgrids offer many advantages including higher end-to-end energy efficiency and easier integration of modern energy resources[2] in comparison to conventional AC microgrids. Energy efficiency improvements are gained because such systems do not suffer from skin effect and fewer conversion stages are required [3]. Additionally, DC MGs provide a simpler platform for the integration of state-of-the-art renewable technologies through efficient power electronics[2], including wind/PV resources, energy storage systems and electric vehicles, etc.

To date, DC distribution networks have not been widely used in public power systems. Their applications are constrained to small-scale electricity networks such as telecommunications, aircraft, and marine power systems[3]. The main obstacles of commercial DC distribution networks have been expensive converters and the lack of direct consumers of DC power. However, recent trends show that costs of PECs are decreasing and user demand for DC power is increasing, raising the viability of near term future DC MGs[4].

One of the remaining challenges is the development of effective DC protection schemes that are designed for multi-terminal HVDC distribution networks[3]. The main difficulty results from the unconventional fault current response of a DC system, which creates two issues for protection. The first relates to the discharge of filter capacitors in response to a short circuit. This causes a rapidly increasing transient fault current peak which presents a damage risk to any electronic components in the fault path if not interrupted by fast acting DC protection. The other issue is that the DC fault current will not necessarily have zero crossing points for easier current interruption, requiring the use of large circuit breakers. Even though many researchers have made substantial efforts in developing theoretically effective DC MG protection strategies, few of them consider the metrology requirements for practical implementation.

This paper will study the fundamental characteristics of DC faults verified using a DC MG model, and derive the new metrology requirements of recently proposed LVDC protection schemes. Section 2 will review the theoretical derivation of DC-side fault transients, and analyse the disruptive impact of PECs on fault current transient behaviour. Section 3 will then classify and review the existing state-of-the-art protection schemes in terms of their fundamental operating principles. Finally, a mathematical analysis of the metrology requirements of each category of protection schemes is performed.

2 DC fault behaviour in DC microgrids

To design effective protection strategies for interconnected DC networks and assign measurement requirements for specific protection schemes, a review of DC-side short-circuit fault behaviour of converter-fed DC MGs is required. Taking a Voltage Source Converter (VSC) fed network as an example, this section will review the theoretical derivation of the DC-side short-circuit fault response. Subsequently, a case study using a DC MG model built in MATLAB/Simulink is conducted to analyse the disruptive impact of PECs on fault current transient behaviour.
2.1 Review of DC short-circuit theory

Fig. 1 illustrates an equivalent model of a pole-to-pole short-circuit fault [4] whilst Fig. 2 shows the voltage and current responses to a range of fault resistances. The fault response can be divided into three stages as proposed in [5].

During Stage 1, a high-magnitude current transient caused by the discharge of the capacitors occurs, lasting from the fault initiation to the zero-voltage condition. This behaviour is evident in Fig. 2. The mathematical derivation of this current response can be obtained from the equation of an RLC circuit

\[
\frac{d^2i(t)}{dt^2} + \frac{R}{L} \frac{di(t)}{dt} + \frac{1}{LC} i(t) = 0, \tag{1}
\]

such that

\[
i(t) \approx \frac{v_c(0)}{L\omega_d} e^{-\alpha t} \sin(\omega_d t), \tag{2}
\]

where \( R, L, C \) are the equivalent resistance, inductance and capacitance of the fault path; \( v_c(0) \) is the pre-fault voltage on the capacitor; \( \alpha \) is the damping factor defined as \( \alpha = R/2L \); \( \omega_0 \) is the resonant radian frequency defined as \( \omega_0 = 1/\sqrt{LC} \); \( \omega_d \) is the damped resonant frequency defined as \( \omega_d = \sqrt{\omega_0^2 - \alpha^2} \). The peak of the current profile occurs during this stage. Before this, the protection should operate in order to avoid exposure to excessive fault current magnitudes. However, this can be particularly challenging to achieve because the available time window of protection operation is very narrow. According to (2), for severely low resistance faults, the rate of change of current can be derived by

\[
\frac{di(t)}{dt} \approx \frac{v_c(0)}{L} \cos(\omega_d t), \tag{3}
\]

where the peak point can be approximated as \( \frac{\pi}{2\omega_0} \frac{v_c}{V_{dc}} \).

Stage 2 can be defined as the freewheeling stage, lasting from the zero-voltage condition to the steady-state current condition. For lower impedance faults, an underdamped current response is realized in which the fault current circulates through the antiparallel diodes within the converter, as illustrated in Fig. 1. This behaviour presents a significant risk of damage to components if the fault is not removed from the circuit by the protection devices prior to this stage [5].

Stage 3 is the grid feeding stage. After the steady-state current condition is reached, the primary side of the converter provides the fault current contribution through the antiparallel diodes of the rectifier [5].

2.2 Case study: short-circuited behaviour of a multi-terminal DC microgrid

This subsection presents a case study to compare the theoretical fault response of a simplified RLC circuit, presented in Section 2.1, to the fault response of a short-circuited DC MG model.

In a multi-terminal DC MG, it can be assumed that the current infed from a network-interfaced VSC is not disabled immediately following a fault. Furthermore, DC MGs are likely to integrate additional PECs involving more complex filter arrangements, such as LC circuits, with unknown fault response characteristics. To investigate the fault behaviour of such interconnected DC systems, a representative model of a DC MG was built within the MATLAB/Simulink environment. A diagram of this system is presented in Fig. 3.

In Fig. 3, the DC MG is connected to the AC utility with a 2-level bi-directional AC-DC VSC [4], regulating the link voltage to +/-375 V on the DC-side. The model of the photovoltaic (PV) system is based on the configuration presented in [6] and utilizes a boost converter to regulate the panel voltage at 54 V to achieve maximum power transfer. The battery array (10 x 12 V) is based on the dynamic model presented in [7], and uses a Dual Active Bridge (DAB) converter [8] to achieve bi-directional power transfer. The electronic load employs a buck converter [4], representing a typical constant voltage load requiring high-quality power. Each of the components connects to the bus through a pair of cables with different distances as shown in Fig. 3.

For each branch of the DC MG, the simulated fault current in response to a 1 mΩ fault on the main distribution busbar is recorded and is compared to the theoretical waveform obtained using equation (2). Taking the AC grid interface branch as an example, the comparison illustrated in Fig. 4 indicates that the fault current behaviour prior to the occurrence of the first peak shows good alignment.
contribution towards the first current peak may not be valid. In conditions, this assumption of negligible converter source power quality regulation and/or higher impedance fault that for high bandwidth power sources typically employed for capacitor discharge and as such can often be neglected. Note current is significantly greater than that of a dc side filter typically the time constant associated with this source of fault first current peak associated with the capacitor discharge.

low-impedance fault does not impact on the magnitude of the b. The converter contribution of fault current in response to a RLC circuit.

reliably approximated by the presented analysis of the nearest branches of the DC MG, the transient fault current can be sufficiently decoupling between the responses of individual For low impedance short circuit faults, where there is a following can be deduced:

a. For low impedance short circuit faults, where there is a sufficient decoupling between the responses of individual branches of the DC MG, the transient fault current can be reliably approximated by the presented analysis of the nearest RLC circuit.

The close similarity between theoretical calculation and simulation result indicates that the capacitor discharge dominates the fault current transient. Accordingly, the following can be deduced:

a. Wide measurement bandwidth. To ensure the measured current is sufficiently accurate to the real fault current, the bandwidth of measurement must be higher than the fault current bandwidth. The highest fault current bandwidth appears in the condition of a short-circuit fault \( (R = 0) \), that is \( \omega_0/2\pi \), typically 200Hz.

### Table 1. Comparison of theoretical and simulated peaks.

<table>
<thead>
<tr>
<th>Branch</th>
<th>Theoretical Calc.</th>
<th>Simulation</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Grid</td>
<td>(0.69 ms, 672A)</td>
<td>(0.77 ms, 703A)</td>
<td>(10%, 4%)</td>
</tr>
<tr>
<td>Regular Load</td>
<td>-</td>
<td>(0, 18A)</td>
<td>-</td>
</tr>
<tr>
<td>PV Array</td>
<td>(0.52 ms, 1122A)</td>
<td>(0.52 ms, 1133A)</td>
<td>(0, 1%)</td>
</tr>
<tr>
<td>Battery Array</td>
<td>(0.26 ms, 3134A)</td>
<td>(0.25 ms, 3039A)</td>
<td>(4%, 3%)</td>
</tr>
<tr>
<td>Const. Volt. Load</td>
<td>(0.91 ms, 369A)</td>
<td>(0.91 ms, 360A)</td>
<td>(0, 3%)</td>
</tr>
</tbody>
</table>

Further analysis presented in Table 1 summarizes the comparison of simulation and theoretical results of peak magnitude and peak time for the fault current measured at each branch. The results obtained show that the errors of all theoretical predictions are less than 10% from that of the simulated responses.

3 Study of state-of-the-art protection schemes

Recently, many researchers have proposed a number of tailor-made protection schemes for DC MGs. In terms of their fundamental principles, this section will review and classify state-of-the-art protection schemes, and investigate the corresponding challenges of measurement in practical applications for each classification.

#### 3.1 Type I: Instantaneous overcurrent protection

Before the concept of DC MGs was proposed, there already existed many small-scale DC electricity applications such as the wiring and electrical equipment for vehicles, requiring protection solutions. These were mainly realised with instantaneous overcurrent protection devices, such as fuses and electromagnetic switches. Such devices require no separate components for measurement, relay processing, and current breaking, however, the drawbacks are also obvious. On one hand, these devices are difficult to coordinate for backup protection, and cannot realise large-scale network protection. On the other hand, these devices are frequently employed effectively in battery-based DC networks, but the protection speed is not fast enough that it can be applied in VSC-based network protection, as described in Section 2.1.

After the invention of solid-state switches, such as Thyristor ETO, MOSFET, IGBT, etc., ultra-fast protection was achievable. The work presented by Mahajan and Baran in represents one of the most comprehensive efforts to design a protection scheme for a VSC interfaced network. For the issue of capacitive discharge, the authors propose the use of instantaneous overcurrent protection for solid-state power electronic switches to interrupt capacitive discharge currents. This is achieved through the connection of an ETO device in series with the capacitive element, as shown in Fig. 5. The operating principle is based on the current sensing of the ETO which is compared to a threshold. When the capacitor current crosses this threshold, a hard turnoff is initiated which limits any further increase and interrupts the current in \( 3 - 7 \, \mu s \).

However, in practical applications, it is difficult for the measurement sensors to reliably detect the transient fault current. Based on the description in the previous section, the current sensor must possess the following two features:

a. The converter contribution of fault current in response to a low-impedance fault does not impact on the magnitude of the first current peak associated with the capacitor discharge. Typically the time constant associated with this source of fault current is significantly greater than that of a dc side filter capacitor discharge and as such can often be neglected. Note that for high bandwidth power sources typically employed for power quality regulation and/or higher impedance fault conditions, this assumption of negligible converter source contribution towards the first current peak may not be valid.

![Fig. 3. Diagram of a DC microgrid.](image)

![Fig. 4. Comparison between the theoretical fault response and simulation results of DC MG fault response at grid feeder.](image)

![Fig. 5. ETO-based capacitive discharge circuit breaker](image)
b. High sampling frequency. As the numerical comparison is conducted by a digital processor, the A/D converter must utilise a high sampling frequency for taking fast protection actions. The sampling time setting depends on the peak time and the number of sample captures required before the time of current peak. Defining the desired number of samples as N, the minimum sampling rate, $f_s$, can be derived, such that

$$f_s = \frac{N}{0.25T_0} = \frac{N}{0.5\pi \sqrt{LC}}$$

(4)

For example, assuming the natural frequency of a fault is 250 Hz ($T_{peak} = 1\ ms$), and the desired number of samples before the peak current is 1000, the minimum sampling rate is 1 MHz. Whilst this approach is suitably fast acting to solve the issue of capacitive discharge for the network described within this paper, the approach is far less effective when higher levels of protection selectivity are desired. That is, ensuring that only the local protection operates for a fault at a particular location in the network. To solve this issue, differential and non-unit protection schemes are proposed.

3.2 Type II: Protection schemes based on differential measurement

A method of high-speed differential protection for smart DC distribution systems is proposed by Fletcher in [10]. It utilizes the natural characteristics of DC differential current measurements to significantly reduce fault detection times, and hence meet requirements for DC converter protection (2ms). This method measures the boundary currents of a protected zone and utilizes a communication link to compare the currents based on Kirchhoff’s current law, such that

$$\Delta i = i_1(t) + i_2(t).$$

(5)

Fig. 6 illustrates the schematic diagram of the internal and external faults. When the sum of currents is greater than a threshold setting, it indicates that a fault exists within the protected zone. When the sum is a low value, it indicates that the network is healthy or there exists an external fault for which the local protection should keep stable. This method offers ultrafast protection with effective selectivity. However, this method requires a large number of SSCBs and communication links with the ensuing high installation costs. Additionally, it does not inherently provide backup protection in the event of device trip-failure.

To overcome the issue of no backup protection, Monadi reinforced this method with a zonal design [11], as shown in Fig. 7. This scheme conducts a current comparison not only between the nearest relays but also between further relays in the event of a failure of low-level zone protection. However, in order to realise effective backup protection, the protection devices have to complete the progress of fault detection, attempting operation in Zone 1, detecting the failure of operation, attempting operation in Zone 2, etc. in the very narrow time window. Therefore, it is challenging to implement this protection scheme in practice.

As for the issue of requiring a large number of SSCBs, Monadi also proposed a centralised protection strategy, as shown in Fig. 8. This scheme only utilizes SSCBs at the boundaries of large zones and terminals of VSCs, while applying only common mechanical isolators on the distribution lines [12]. As a fault occurs, the SSCB operates rapidly to isolate the faulted zone, while the isolators locate the faulted line based on directional-based protection scheme for LVDC distribution networks [13], as shown in Fig. 9. This scheme employs a centralised protection device to gather and process data on current directions rather than values. When the currents on the two ends of a line are detected as flowing in opposite directions, it indicates that a short-circuit fault has occurred within the zone. The centralized digital relay unit can offer effective backup protection, but also poses a risk, as it is a single point of failure of the protection system. Additionally, since the protection is only based on current direction, it may be ineffective for detecting high-impedance faults.
as shown in Fig. 10. According to (3), if the rate of current synchronization errors can cause significant differential errors, the change of current at the initial current may be as narrow as 1μs. Table 2 summarises the advantages and drawbacks of the state-of-the-art schemes described in this paper, and the challenges of measurement of each.

At the initiation of a short-circuit fault, that is \( t = 0^+ \), the term \( i_L(t)R \) is approximately zero and can therefore be neglected. Accordingly, the cable inductance, which represents the distance from the capacitor to the fault location, can be derived by the pre-fault voltage and the initial \( di/dt \) measurement, where

\[
L \approx \frac{v_{cp}(0^+)}{di(0^+)/dt} \tag{8}
\]

Since this method utilises the initial characteristics of the fault transient, it can theoretically estimate fault distance within the first two samples after fault initiation, enabling the operation of protection at lower current levels. Additionally, this protection method can offer effective backup protection by discriminating the fault locations. However, the drawbacks include that this protection principle does not allow any shunt capacitors to be connected which are commonly employed in PECs and electronic loads, causing the protection to be ineffective in the event of a failure to accurately detect the initial \( di/dt \) value.

In order to overcome the risk of missing the initial \( di/dt \) measurement, Feng has reinforced the scheme with an optimised approach [15]. Measuring voltage, current and \( di/dt \) every 20-100 μs, the simultaneous equations can be solved to determine \( R \) and \( L \), where by

\[
\begin{bmatrix}
\frac{di}{dt} \\
\frac{di}{dt}
\end{bmatrix}
= \begin{bmatrix}
i(1) \\
i(0)
\end{bmatrix} A^{-1} B
\]

This method not only overcomes the risk of missing the initial fault point, but also is capable of distinguishing low-resistance and high-resistance faults. However, as a downside to this method is that it takes a long time to detect a fault. Other methods based on \( dv/dt \) and \( d^2i/dt^2 \) have also been proposed in the literature but have not been proven in practice.

The metrology requirements of Type III protection schemes are particularly challenging because derivative computation is extremely sensitive to very small noise. So, signal conditioning is required for optimising the derivative computation [16]. Accordingly, the appropriate sampling time should first be selected. Extremely short sampling time will magnify the noise by numerical derivative computation, while excessively long sampling times will result in attenuated \( di/dt \) results and time delays. A digital low-pass filter may be needed to constrain the high-frequency noise before the numerical derivative computation.

### 3.4 Summary

Table 3 summarises the advantages and drawbacks of the state-of-the-art schemes described in this paper, and the challenges of measurement of each.
This paper has categorised state-of-the-art protection schemes for DC MGs and derived new metrology requirements for each, with a focus on the measurement challenges associated with practical implementation. It was found that instantaneous overcurrent protection requires wide-bandwidth measurement sensors and ultrafast sampling rates to avoid missing the initial fault current peak. Differential protection schemes require very accurate time-synchronised measurements with minimal time synchronisation error that may cause protection mal-operation. Non-unit protection schemes based on the rate-of-change of local measurands to avoid the use of communication links were also presented. However, numerical derivative computation is very sensitive to noise so signal conditioning should be applied, including selecting appropriate computational time-steps and effective low-pass filters.

The authors believe that the findings in this paper place an emphasis on redefining the focus of the dc protection research community. Whilst current efforts focus on addressing the limitations in state-of-the-art solid-state and mechanical technologies (e.g., fault withstand in PECs, current interruption in SSCBs, selectivity/speed of breakers), this paper has shown that this approach may result in unrealisable solutions because the metrology requirements have not been sufficiently considered. The findings presented provide a strong argument to consider metrology capabilities/limitations as part of the technology solution in order to realise impactful and game-changing research. In the future, the authors plan to demonstrate the value of this new perspective by delivering near-term realisable, novel DC MG protection solutions shaped by practical measurement constraints.

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<table>
<thead>
<tr>
<th>Type II: Differential protection</th>
<th>Type</th>
<th>Scheme Name</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Measurement Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential with backup</td>
<td>Type I: Overcurrent</td>
<td>Fuse/EM switch</td>
<td>Compact</td>
<td>Slow</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ETO-SSCB</td>
<td>High-speed</td>
<td>Difficult in realising selectivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Differential</td>
<td>High-speed</td>
<td>Provides no backup protection</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Differential with backup</td>
<td>High selectivity</td>
<td>Require large number of SSCBs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Centralised</td>
<td>Less usage of SSCBs</td>
<td>Need communication links</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Directional</td>
<td>Less data transmission</td>
<td>Need communication links</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Initial ( \frac{d}{dt} )</td>
<td>High-speed</td>
<td>Risk of missing initial sample</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple ( \frac{d}{dt} )</td>
<td>Higher reliability</td>
<td>Shunt capacitor not allowed</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Summary of protection schemes.

4 Conclusion
This paper has categorised state-of-the-art protection schemes for DC MGs and derived new metrology requirements for each, with a practical focus on the measurement challenges associated with practical implementation. It was found that instantaneous overcurrent protection requires wide-bandwidth measurement sensors and ultrafast sampling rates to avoid missing the initial fault current peak. Differential protection schemes require very accurate time-synchronised measurements with minimal time synchronisation error that may cause protection mal-operation in the event of external faults. Particularly, in a compact DC network where a high \( \frac{d}{dt} \) exists, this requirement may be too difficult to achieve practically. Non-unit protection schemes based on the rate-of-change of local measurands to avoid the use of communication links were also presented. However, numerical derivative computation is very sensitive to noise so signal conditioning should be applied, including selecting appropriate computational time-steps and effective low-pass filters.

The authors believe that the findings in this paper place an emphasis on redefining the focus of the dc protection research community. Whilst current efforts focus on addressing the limitations in state-of-the-art solid-state and mechanical technologies (e.g., fault withstand in PECs, current interruption in SSCBs, selectivity/speed of breakers), this paper has shown that this approach may result in unrealisable solutions because the metrology requirements have not been sufficiently considered. The findings presented provide a strong argument to consider metrology capabilities/limitations as part of the technology solution in order to realise impactful and game-changing research. In the future, the authors plan to demonstrate the value of this new perspective by delivering near-term realisable, novel DC MG protection solutions shaped by practical measurement constraints.

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