FAULT CURRENT LIMITING CIRCUIT BREAKER IN DISTRIBUTION SYSTEMS

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ABSTRACT

The Powerful CB project is a collaboration between UK Power Networks (UKPN) and ABB to develop and demonstrate an 11 kV Fault Current Limiting Circuit Breaker, FLCB, in an existing UK Power Networks substation. The technology utilized in the FLCB is a combination of power semiconductors and mechanical switches, enabling fast limitation, low losses and compact installation. In operation it limits a prospective fault current of 25 kA rms to maximum 13 kA peak in less than 1 ms after the trip signal.

INTRODUCTION

In the UK, progressively more Distributed Generation, DG, is being installed and connected to the distribution grid. Specifically, the Mayor of London expects 25 per cent of the heat and power used in London to be generated through the use of localised decentralised energy systems by 2025 [1]. It is expected that this will encourage combined heat and power, CHP, and district heating for new developments. This fact, in addition to the interconnected nature of London’s network, leads to increased fault levels, which in some cases can be driven beyond the capacity of the existing switchgear components. The existing solution is to replace and upgrade switchgear, which is capital intensive and therefore a barrier for the connection of further generation. By installing a much faster, current limiting, circuit breaker in strategic positions in the distribution grid, the existing equipment does not need to be replaced.

Additionally, there are scenarios in which more generation connections drive fault levels beyond capacity only under abnormal running arrangements. Generators are asked to shut down if those abnormal running arrangements are occurring due to maintenance or other reasons. These are called inhibit schemes. An FLCB can allow the generator to continue producing and support the network even under these abnormal running arrangements.

FAULT CURRENT LIMITER, FCL

In conventional circuit breakers, the current is interrupted by opening a contact gap, using mechanical contacts, and at current zero the arc is extinguished. This way, the full fault current will flow through the breaker and the rest of the network for 50-100 ms. If all different substation and network components are designed for this current, the fault is cleared safely. However, if there is a risk that this design limit will be exceeded, other measures needs to be implemented. One possibility is to introduce a device which will limit the fault current below the critical design value of the power grid, i.e. a Fault Current Limiter (FCL). An FCL needs to be very fast and limit the current within milliseconds, rather than tens of milliseconds, since the current derivative is usually very high during a fault.

The concept of fault current limiting in power networks has been around for decades and several different technologies have been explored.

Two different basic concepts have been identified. Either a dynamic impedance is introduced, or a very fast interruption is performed to clear the fault before the current peak. Dynamic impedance devices have low impact on the grid under normal operating conditions but will rapidly increase their impedance during a fault event, limiting the maximum peak current. Examples of this type are electromagnetic or superconducting fault current limiters [2]. Their main characteristic is that they limit the maximum peak current but do not interrupt the current completely. After the fault is cleared, the impedance is restored and nominal operation may continue. A common disadvantage is that they are, in most cases, large, heavy and in the superconducting case require advanced low temperature cooling. The advantage of this technology is that solutions are intrinsically fail-safe because most credible failure modes result in the device failing to a high impedance state.

The second class, fast interrupters, limit the fault current by interrupting the current before it reaches the critical design limit. This should be done in a few ms. One example of this type is the already commercially available I_s-limiter, [3]. The I_s-limiter consists of a fast detection device and a fast commutation switch in parallel with a fuse. When a fault is detected, a pyro device opens the switch, which commutates the current into the fuse, melt the fuse and the current is interrupted. After the interruption the fuse and pyro device need to be replaced.

Another possibility for fast interruption is the introduction of power semiconductors. They have the capability to interrupt currents within micro seconds and may easily be switched back on remotely after the fault is cleared. This is an advantage over fuse technology, which needs manual replacement after operation. Power semiconductors on the other hand are expensive and the high on state losses require additional cooling, especially at higher nominal currents.

In the Powerful CB project, a fault limiting circuit breaker will be installed in a London substation. The FLCB has multi-shot capability and does not require water cooling as requested. To achieve this, a hybrid solution is suggested, combining the fast switching of power semiconductors and the very low losses of mechanical switches. The hybrid concept also presents a more compact solution than the passive dynamic impedance devices. The compact size is a major advantage of the hybrid FLCB making it possible to implement it in the London area and other densely populated urban areas where other technologies are difficult to adopt.

During the submission process of the project a detailed analysis of various concepts for current limitation were evaluated and compared with the requirements for this application. A condensed summary is shown in table 1.

Solution	ABB FLCB	AMAT FLCB	Active Fault De-coupler	I_s-limiter	Current limiting reactor / high impedance transformer	Saturated/Shielded Core FCL	Resistive Superconducting FCL	Hybrid Power Electronic FCL	RESPOND FCL Service	RESPOND Adaptive Protection	Busbar Splitting
"break" fault level reduction	High	High	High	High	Moderate	Moderate	Moderate	Moderate	High	High	High
"make" fault level reduction[21]	High	High	High	High	Moderate	Moderate	Moderate	Moderate	None[22]	None[22]	High
Impact on customers	No[23]	Yes[24]	No	No	No	No	No	No	Yes[25]	No	Yes
Time to restore to secure running arrangement	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	> 1 hour[26]	Instantaneous	Instantaneous	< 3 min	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	Requires permanent running in insecure arrangement
Operation and maintenance impact	Low	Low	Low – Medium	High	Low – Medium	Low – Medium	Low – Medium	Low – Medium	Low	Low	Low
Physical space required	Medium	Medium	Large	Medium	Large	Large	Large	Large	Negligible	Negligible	Nil
Losses / quiescent power consumption	Negligible	Low	Significant	Nil	Significant	Significant[27]	Significant	Significant	Nil	Nil	Nil
Requires delayed fault clearance times	No	No	No	No	No	No	No	No	Yes	Yes	No
Showstoppers for use in Central London	None	None	Too big	Compromises security of supply	Too big	Too big	Too big	Too big	Doesn't reduce "make" FLs	Doesn't reduce "make" FLs	Compromises security of supply

Table 1. Evaluation of various concepts for current limitation in distribution systems [4].

POWERFUL CB

Hybrid FLCB

The hybrid fault current limiting circuit breaker, FLCB, is previously mentioned in literature, [5]. The device described here is a further development of the hybrid FLCB in [5] and is specially designed for the application requested by UKPN. The Hybrid FLCB has three major branches - power electronics, fast mechanical switch and surge arrester.

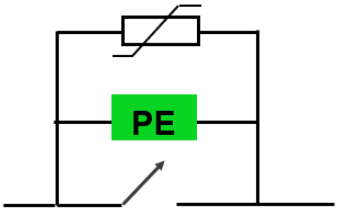

Figure 1. Principle of the hybrid fault current limiter.

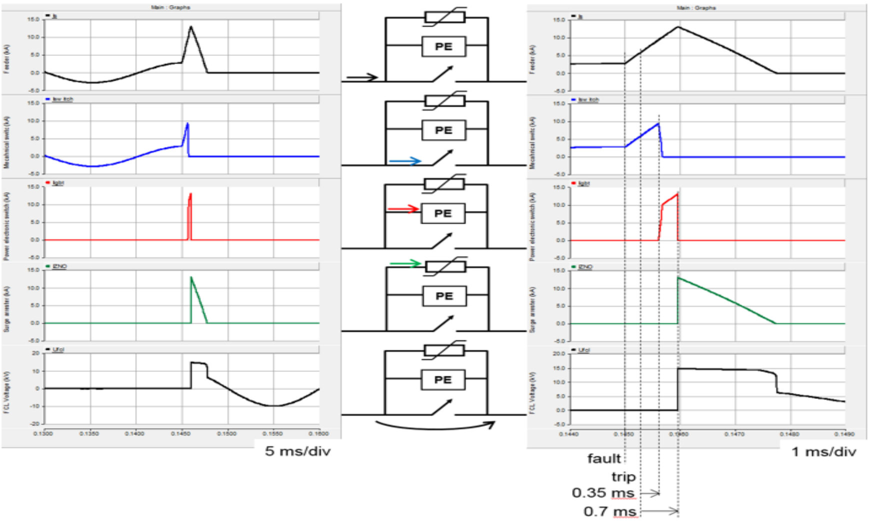

Figure 2. Simulated currents through and voltage across the FLCB and the operation times.

In nominal operation the current flows through the mechanical switch, with very low losses. At the detection of a fault the switch is opened, and the arc voltage transfers/commutates the current to the power electronics (PE). In a second step the PE is turned off and the current is commutated to the surge arrester. The arrester is designed to create a counter voltage, larger than the system voltage, which will force the current to zero. A second important design parameter for the surge arrester is the ability to dissipate the stored inductive energy during the fault interruption. For further understanding of the interruption procedure see figure 2. To illustrate the interruption in comparison to the full prospective fault current a conceptual graph is shown in figure 3.

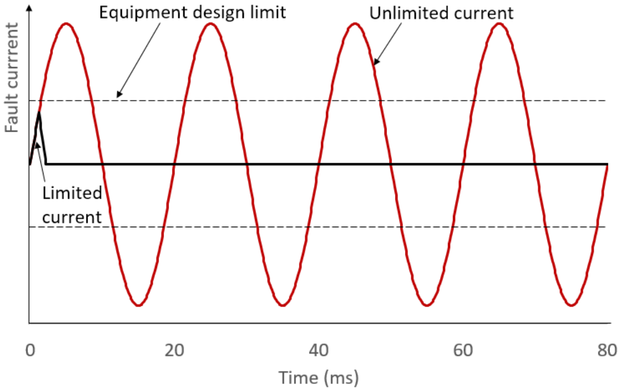

Figure 3. Fault current limitation using a hybrid FLCB.

Fast Commutation Switch

To be able to implement the hybrid concept with interruption times below 1 ms, which would be necessary for a 25 kA prospective fault current, an ultra-fast mechanical switch is essential. Looking at the interruption sequence in figure 2 it is understood that the contact separation needs to take place in approx. 0.35 ms. This is accomplished by combining a tailor-made, light weight, contact system with an electro-magnetic drive system. This provides the proper reaction time and acceleration.

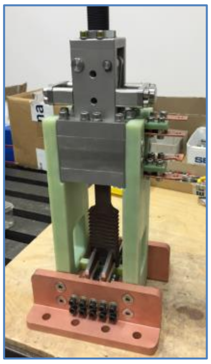

Figure 4. One of the Fast Commutation Switches used for the Powerful CB.

Performance

For the pilot installation at UKPN the basic requirements for the FLCB are the following:

Nominal voltage	11 kV (12 kV)
Nominal current	2000 A
Prospective fault current:	25 kArms
Limited peak current	13 kA
Interruption time	< 1 ms

Actual grid values, design levels in parenthesis.

In an earlier project, [5], it was shown that these requirements are achievable with the suggested hybrid concept. During the project execution several tests were conducted to verify the performance. An example of an interruption test with full prospective fault current is displayed in figure 4.

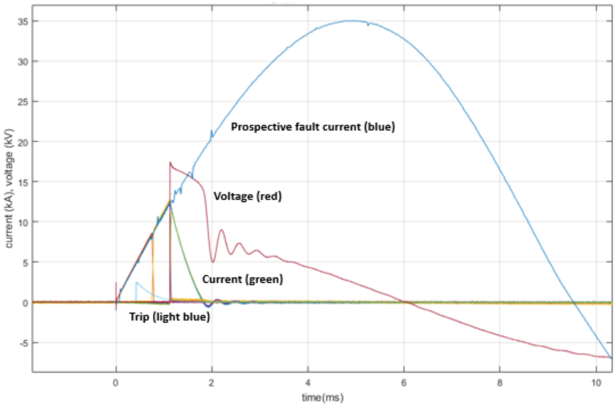

Figure 5. Verification testing of the FLCB.

To ensure that the maximum allowed fault current in the grid is never exceeded, taking into account the maximum current derivative dI/dt for a 25 kA prospective fault current, approx., 11 kA/ms, the FLCB needs to interrupt the current within less than 1 ms after detecting the fault. This puts extremely high demands on both the detection system and the operation of the device. To get a fast and reliable fault detection the well proven I_s-limiter control unit is used. In the Powerful CB project, it continuously measures the absolute value of the current and within a few micro-seconds sends a trip signal to the control system of the FLCB when the pre-set value is exceeded. Since the FLCB consist of several active devices a very fast and accurate control system is implemented for the operation sequence. It is required that the time resolution of the control system is in the micro-second range.

IMPLEMENTATION IN THE GRID

The main purpose of the FLCB is to limit the maximum fault current in the grid, or a substation. To accomplish this functionality there are different ways of introducing it onto the grid. Some examples are shown in figure 6 and 7.
In a configuration shown in figure 6, when one transformer

is taken offline due to a fault or planned maintenance, the busbar sections are connected to run solid to support the load without overloading the remaining transformers. This however can increase fault levels up to or above the design limit and usually requires generation to be disconnected to reduce fault levels. If an FLCB was connected as a bus-coupler instead of a standard circuit breaker, this would reduce the fault level contribution from one bus section to another and allow generation to stay connected during these abnormal running arrangements. The reason is that the FLCB will separate the busses in less than 1 ms during a fault, with the result that very limited fault current will be transferred from one bus section to another. This creates maximum flexibility in the running arrangement with limited risk of over-stressing the substation and generators can stay connected.

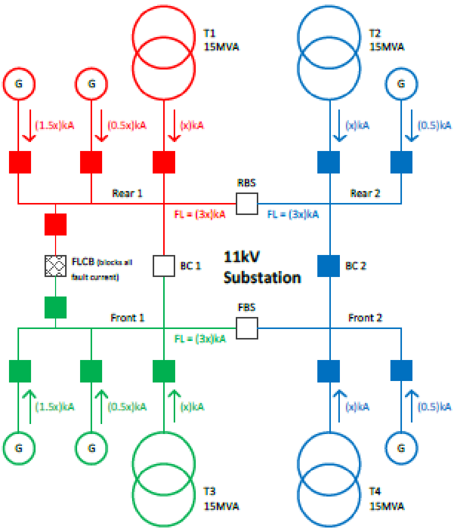

Figure 6. FLCB introduced as a bus coupler.

In an alternative configuration the FLCB is placed on one, or more, of the incoming feeders, see figure 7. In this arrangement, the FLCB disconnects the incoming feeders connected via FLCB during a fault so that the fault contribution is limited effectively based on the high performance of the device. Therefore, also this configuration provides additional fault level headroom making it possible to connect more distributed generation without exceeding the fault level design limit.

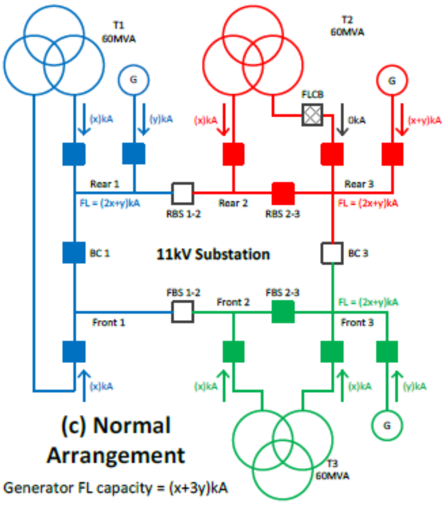

Figure 7. FLCB placed on one of the incoming feeders.

Another option, not pursued in this project, is the possibility to connect the FLCB directly on a generator feeder. In case of a fault, the current from the generator would be limited within 1 ms, not adding any significant contribution to the total fault current.

PILOT INSTALLATION

As mentioned earlier, in addition to the performance requirements given above, several other features shall be verified during the project according to the NIC submission, [4]. These are, for example, the ability to auto-close on demand and no water cooling. Even though this is a pilot installation the device still needs to comply with the relevant standards and will be tested accordingly.
Available power semiconductors, for the requested current ratings, still have fairly low voltage rating. To achieve the proper performance several devices needs to be connected in series. Therefore, a modular concept, as shown in figures 8 and 9, was introduced. This design provides significant benefits, such as, scalability and redundancy.

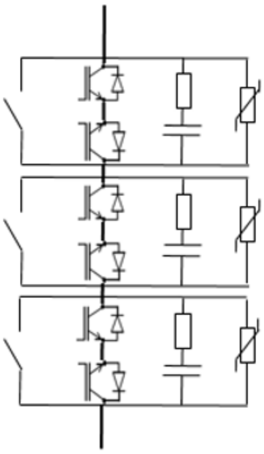

Figure 8. Modular concept of the FLCB for UKPN.

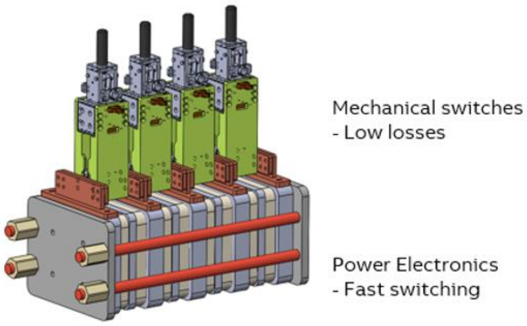

Figure 9. Modular concept of the FLCB for UKPN.

The FLCB concept is more compact than most other alternative fault current limiters. For this specific installation the device will be placed in three standard medium voltage panels, one for each phase. A basic installation set-up is shown in figure 10.

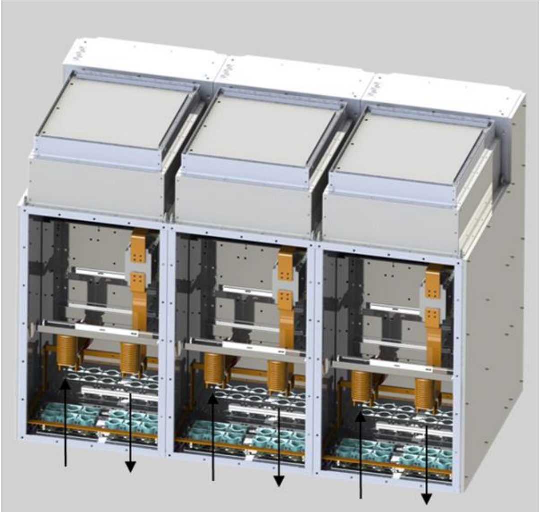

Figure 10. Pilot installation using three MV panels for the FLCB.

The device will be physically installed as a bus coupler in a London primary substation. The site was chosen because it registers a high number of faults per year, there is available space for the installation and the fault level headroom is not far from the design limit. The flexibility of the busbar configuration will allow simulating the operation of the FLCB as an incoming circuit breaker in addition of bus coupler. Therefore, both implementation options can be tested.

SUMMARY

It has been identified that a Fault Current Limiting Circuit Breaker is an attractive alternative compared to upgrading distribution substations when short circuit headroom is shrinking. A hybrid, mechanical and power electronics, fault current limiter concept is presented, which will be built, tested and installed as a pilot in a London substation during 2019. The fast, compact, low loss and multi-shot FLCB makes it possible to run the distribution system at a higher fault level giving better system stability without the need of a complete upgrade of the substation. At the same time the technology enables more flexible and optimized connection of distributed generation and renewable energy sources, independent of existing fault level headroom.
The project is performed in cooperation between ABB and UK Power Networks and made possible through the NIC, Network Innovation Competition, funded by Ofgem. The FLCB for the pilot is designed for 12 kV, 2000 A nominal current and will be tested with a prospective fault current of 25 kA.

REFERENECES

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