Background

Climate change is recognised as a major threat to our planet. Greenhouse gas emissions reduction has been identified as a key measure for mitigating that threat. As of 2019, the UK became the first major economy to be legally bound to reduce its greenhouse gas emissions to net zero by 2050 compared with the previous 2008 target of at least 80% of 1990 levels.

Demand for electricity is forecast to double by 2050, mainly due to the plans for the electrification of transport and heating, during which time existing coal-fired power stations will be progressively decommissioned (1).

The need for low-carbon and sustainable forms of electricity generation become evident, but the connection of such sources onto the electrical system is not always easy despite their assorted benefits. The decarbonisation of the power sector is an important objective, but changes to the electrical network should aim to optimise its operability without adversely affecting its reliability or efficiency.
Introduction

The connection of Distributed Generation (DG) to the electrical system is an intricate matter since various restrictions and constraints might impede it. For every prospective connection, a network operator will need to consider system voltage limits, thermal limits, reverse power flows and importantly system fault levels.

Fault levels are an indication of the magnitude of the fault current that would flow through the system in the event of a short-circuit (fault). Higher fault levels mean greater stress for the power system as substantial magnitudes of fault current could stress and potentially damage critical primary equipment. In the worst-case scenario, the introduction of DG can cause a fault level to be greater than the withstand capacity of the network leading to the failure of the power system and its equipment.

It has been assessed that a large number of Primary Substations across the UK have already started to reach their fault level limits and it is expected that the problem will be exaggerated in areas where the Primary Substations attract new DG and new demand at a fast rate, for instance in dense urban 11kV distribution networks. Generation including synchronous machines, including Combined Heat & Power (CHP), is considered to contribute the most to fault level increases compared to its rating. Inverter connected generation, such as Photo Voltaic (PV), typically makes a lower fault contribution compared to its rating.

Conventional solutions to fault level issues might be implemented to resolve the problem, but they may result in significant disadvantages. For example, network reinforcement can come at a
significant cost (on average £8.5m per substation (5)) and long lead times to complete the work (typically 12-24 months). Passive solutions including higher impedance transformers, network splitting, the application of Current Limiting Reactors (CLR) and connection of DG at higher voltage levels can be associated with lower system reliability, increased operational complexity, high costs, reduced power quality and degraded system stability (2).

**Application of Fault Current Limiting Devices**

*Introduction to fault current limiting devices*

Fault current limiting devices can be the smart solution to the depletion of fault level headroom at Primary Substations across the UK. Under normal system operation, these devices present low impedance to the system, whereas during fault conditions they increase their impedance enough to suppress excessive fault current flow and allow the existing equipment to clear the fault (3). Figure 1 below shows the pre-fault and fault current flow in a simplified system with a fault current limiting device connected.

![Figure 1: Pre-fault system (left), system during fault (right)](image)

The switch represents a short-circuit in the system. Whilst the switch is open, i.e. without a fault in the system, the load current (\(I_{L,fcld}\)) supplied by the source (\(V_s\)) flows through the network impedance (\(Z_s\)), the low fault current limiting device’s impedance (\(Z_{fcld,low}\)) and the load impedance (\(Z_L\)):

\[
I_{L,fcld} = \frac{V_s}{Z_s + Z_{fcld,low} + Z_L} \approx \frac{V_s}{Z_s + Z_L}
\]

nearly as much current as would flow without a fault current limiting device in place (\(I_L\)).
If a fault occurred, the fault current \( (I_f) \) that would flow through the circuit, if no fault current limiting device was in place, would be excessive, possibly destructive to system equipment and a potential safety hazard to personnel. With the fault current limiting device in place, which will have a high impedance during abnormal conditions \( (Z_{fcld,\text{high}}) \), the fault current \( (I_{fcld}) \) is reduced and can be interrupted by the existing circuit breakers.

\[
I_{fcld} = \frac{V_s}{Z_s + Z_{fcld,\text{high}}} << V_s = I_f
\]

### Benefits of fault current limiting devices

Fault current limiting devices can deliver various benefits to power systems including:

- Deferral or avoidance of network reinforcement investment
- Facilitation of connections of low-carbon DG in a timely manner
- Reduction in customer interruptions (CI) and customer minutes lost (CML)
- Long-term sustainability and affordable electricity prices

### Types of fault current limiting devices

There are different types of fault current limiting devices, which base their fault current suppression and recovery on a variety of techniques. The most notable devices are:

- **Solid-state fault current limiters (SSFCL):** they comprise self-commutated solid-state semiconductor devices that can divert the fault current through an energy absorbing resistor or reactor within a few milliseconds (4).

- **Superconducting fault current limiters (SCFCL):** when operating below critical current, temperature and magnetic field thresholds, these devices are in a superconducting state and have essentially zero resistance. When any of the critical thresholds are exceeded, the device enters a state of normal conductivity. The most common types are the resistive SCFCL and the shielded-core SCFCL, which are “quenching” types, and the saturable-core SCFCL, which is a “non-quenching” type (4).

- **Hybrid devices:** they utilise power electronics and a superconducting resistance or inductance to limit fault currents (4).

- **Saturated inductor core devices:** present a low electrical impedance during normal conditions and rapidly increasing higher impedance as it moves out of saturation during a
fault. Saturation of the inductor core is by means of a powered DC coil system or permanent magnets (or a combination of both).

**Introduction to the Passive Magnetic Fault Current Limiter (pmFCL)**

FaultCurrent Limited has designed a fault current limiting device that is quite different in its operation from the devices listed above and that encompasses unique features and advantages.

![Cross sectional view of the pmFCL showing 3 layers of coils and magnets](image)

**Principle of operation:** This device is a passive magnetic fault current limiter (pmFCL) that bases its operation on ceramic ferrite permanent magnets interspersed with current carrying copper windings that bias and saturate the iron (“electrical steel”) core of the device. Thanks to its novel and highly efficient arrangement, the pmFCL presents a low electrical impedance during normal conditions and rapidly increasing higher impedance as it moves out of saturation during a fault.
**Construction:** The pmFCL is a three-phase 11kV device that comprises 8 dry insulated, copper windings for each of the three phases (24 windings in total) wrapped around ferrite magnets. The magnets are arranged in a patented octagonal fashion to comprise each phase. The three phases are then placed on top of each other. The copper windings can be connected in various series and parallel combinations providing flexibility for creating different variants of the pmFCL, namely the 20MVA variant with 4 parallel sets of 2 windings in series (~1,000Amps rated current), the 10MVA variant with 2 parallel branches of 4 windings in series (~500Amps) and the 5MVA version with 1 branch of 8 windings all in series (~250Amps). The pmFCL is rewired from inside to create these variants.

View showing the wiring arrangements for the 20MVA pmFCL
Features – Prevention of demagnetisation

The overall dimensions of the pmFCL are 3.5m x 3m x 3m, while it weighs 57 tonnes in total, with the weight of the ceramic ferrite tiles accounting for 25 of the tonnes.

The pmFCL can act rapidly to increase its impedance in case of a fault, typically within less than 2msec, and can also reset very quickly following clearance of the fault (less than 1msec).

The device is protected by external cladding fitted with several louvers that allow for the natural ventilation and cooling of the pmFCL. This is considered sufficient due to the dry type winding insulation using a combination of high temperature Polyimide and Glass Mica and the strategic distribution of the windings in the pmFCL structure. The windings can withstand a steady-state temperature of 200°C. The winding insulation is typical of the type used in large rotating machines and considered most suitable for the design of distributed windings in the pmFCL.

However, the most important feature of the pmFCL is its patented capability to prevent demagnetisation of the ferrite magnets during the flow of fault current by ensuring that peak field values in the AC windings do not exceed coercive field values in the vicinity of the magnets. Even in the unlikely event of demagnetisation of the permanent magnets, the pmFCL fails safely by adopting its higher impedance state.
Fault current reduction capability (tests at the KEMA Laboratories)

The table below shows the fault current reduction capability of the 20MVA pmFCL 11kV variant as measured in at the KEMA laboratories as maybe required in an 11kV circuit at a Primary substation.

<table>
<thead>
<tr>
<th>20MVA 11kV pmFCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated RMS service current (kA)</td>
</tr>
<tr>
<td>Peak asymmetrical fault current (kA)</td>
</tr>
<tr>
<td>Limited peak asymmetrical fault current (kA)</td>
</tr>
<tr>
<td>Peak asymmetrical fault current reduction</td>
</tr>
<tr>
<td>Symmetrical RMS fault current (kA)</td>
</tr>
<tr>
<td>Limited symmetrical RMS fault current (kA)</td>
</tr>
<tr>
<td>Symmetrical RMS fault current reduction</td>
</tr>
</tbody>
</table>

Table 2: Fault current reduction of the 20MVA pmFCL at the KEMA test laboratory

Photo of the pmFCL at the KEMA fault testing laboratory
The KEMA fault testing applied a 2 full magnitude 3 phase bolted short circuits sequentially to each phase. The fault timing was adjusted to apply the peak (switch closed) current to Phase C initially without the pmFCL in circuit to establish the prospective peak current. Subsequent tests used this prospective peak value as the reference point. A typical fault waveform taken from the KEMA data capture equipment is shown below.

The fault testing included:

a) 2 fault shots per phase applied to each phase in sequence at 50Hz
b) 2 fault shots per phase applied to each phase in sequence at 60Hz

The inductive impedance of the windings were measured after each fault event.
Load flow testing at the Quartzelec test Laboratories

A number of load flow tests were conducted at the Quartzelec test laboratory in Rugby who were able to offer 50Hz and 60Hz AC testing without the use of tuned resonant capacitors banks. The key pmFCL performance parameters were catalogued as a function of load flow current:

(a) Phase impedance  
(b) Harmonic distortion estimates  
(c) Heat rise at rated current  
(d) Heat rise from 80% rated current to 1.5 X overload current  
(e) Power dissipation  
(f) 50Hz AC stray magnetic field at 1 meter  
(g) The acoustic noise level at 1 meter from the pmFCL  
(h) -75KV impulse testing
Results for each of the above parameters tested at Quartzelec’s laboratories outlined below:

(a) The phase impedance follows the expected flat plateau up to the rated current, and then increases as the magnetically saturated inductor blades become permeable for an increasing proportion of the current waveform.

The phase impedance increase can be seen to progress into the fault level region. The 3 fault level results from the KEMA tests can be added to the load flow impedance graph to reveal an increasing impedance with RMS current.
(b) Harmonic distortion estimates can be made from the Quartzelec low voltage testing into a short circuit load and scaled for the full 11KV line voltage.

![Total Harmonic Distortion VS Phase Current in 11KV](image)

(c) Heat rise at the rated current took 28 hours from an ambient of 20 deg C, this long-time constant is a function of the large 57 tonne mass of the pmFCL. A Computational Fluid Dynamics (CFD) model, showing natural convection air inflow (in blue) and outflow (in green) in the figure below, was created to inform the design of ventilation louvres.

![pmFCL heat rise over 28 hours at rated current](image)
(d) Heat rise from 80% rated current to 1.6 X overload current is shown with temperature plots from all 24 temperature sensors i.e. 1 per winding. The plot reveals a 28 deg C rise in 1 hour. The thermal imaging photograph shows the outer casing of the pmFCL at 1600 Amps RMS after 1 hour from a start of 800 Amps RMS.
(e) Low power dissipation has been achieved through careful design of inductor cores and windings. The power dissipation at the rated current of 1kA RMS is 35kW.

![Power dissipation watts graph](image)

(f) The 50Hz AC stray magnetic field, measured at 1 meter, as a function of phase current in the 10MVA configuration during KEMA testing. The stray field at rated in the 10MVA is identical to the stray field in the 20MVA configuration at rated. Note that the current flowing in each inductor is the same in each configuration and that the measured stray field is approximately 10% of a similarly rated primary transformer.

![AC field μT at 1 meter from the FCL graph](image)
The stray DC (static) magnetic field from the bias magnets was measured with test equipment provided by Eriez. This field only extends a short distance from the pmFCL enclosure and is very low because of the cancelation of fields from the “chequer board” arrangement of magnet polarities inside the unit.

<table>
<thead>
<tr>
<th>DC flux field measurement no.</th>
<th>Gauss</th>
<th>Distance from FCL wall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>900</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>3</td>
<td>130</td>
<td>300</td>
</tr>
</tbody>
</table>

(g) The acoustic noise level at 1 meter from the pmFCL was measured at the KEMA labs using the 10MVA configuration. The 20MVA could not be re-measured in this instance because of the excess noise levels in the Quartzelec laboratory from the rotating machine converters in close proximity to the testing. These results indicate less than 75dBa at the rated current and the improved inductor designs in the 20MVA unit would be expected to be much quieter.
(f) 75KV impulse testing

-75KV impulse testing was successfully completed using a certified test house (SamTech). 3 full magnitude shots were applied to each phase to check for full insulation integrity. A typical waveform is shown below:

![Waveform Image]

**Figure 4b.**
Phase A, 1st full-level full impulse (100%).

Actual voltage
8.52 × 8740 = 74.5 kV

Front time: 1.54 μs
Time to half-value: 41.1 μs

Advantages of pmFCLs vs Current Limiting Reactors (CLRs)

The main disadvantages of the CLR could be considered under normal system operation. If the CLR was assumed to have a resistance of 0.66% on rating (0.0403Ω) and chosen to have a reactance of 6.6% on rating (0.403Ω) to give the required reduction for the comparison, while the pmFCL under normal conditions would present a much lower impedance of 0.187Ω. This equates to a power transfer advantage of the pmFCL over the CLR of approximately 240KW in to a low power factor load. (See also Case Study 2 for a theoretical comparison, a 20MVA 11kV CLR with a typical resistance of 0.66% and a chosen reactance of 6.6% on rating).
**Summary of advantages of the pmFCL**

- Entirely passive and autonomous device (“fit & forget”)
- No requirements for power supply to saturate the core, no auxiliary systems necessary
- Negligible maintenance and operational costs
- Protection from demagnetisation and fail-safe capability
- Operates rapidly (<2msec) and recovers automatically (<1msec)
- Minimal losses and voltage drop under normal operation (36kW and <0.3% respectively for the 20MVA pmFCL)
- Low harmonic distortion under normal conditions (THDv ≈ 0.3%)
- Quick to install with minimal disruption, self-contained unit
- Modular construction, combination of multiple devices possible if necessary
- Versatile winding connections allowing three variants (20MVA, 10MVA and 5MVA)
Applications of the pmFCL

**Typical applications:** The installation of a pmFCL in an 11kV system can be considered under several possible scenarios due to its versatility. The most typical applications are depicted below in Figure 3 and are related to bus-section installations (a), installations coupled with transformers (b) and installations associated with DG (c).

![Figure 3: Typical pmFCL applications](image)

Other possible applications include:

- Network coupling
- Ring circuit formation
- Coupling with fault-contributing loads

**Considerations for selecting the most beneficial application**

Protection engineers and system planners need to consider the system and their objectives carefully before selecting the appropriate type and location for the pmFCL installation. Things to consider include:

- The prospective unlimited fault current due to planned system changes, e.g. new generation connection, new interconnection etc.
- The fault level decrease necessary to accommodate the system changes
- The pmFCL operation and recovery times and how they coordinate with system protection
- Steady-state system impedance increase, voltage drop, power losses and potentially additional harmonic distortion
- Fail-safe measures and security of supply
Simulation Tools

**IPSA2 and PowerFactory Scripts**

Plug in modules can be provided for the two most popular power network analysis tools (IPSA2 and PowerFactory). Within the plug-in models, both Load Flow and Fault Level Analysis is provided based upon the actual pmFCL impedance relationship with current and the fault current impedance extracted from KEMA testing. An iterative convergence process has to be used in order to calculate the impedance presented by the pmFCL during a fault event. The general procedure would be:

1) Use the load-flow model to set-up pmFCL model
2) Apply a three-phase fault at a particular location and note down the AC RMS current flowing through the pmFCL branch during at a particular time during the fault conditions.
3) Using the value of the pmFCL branch RMS current flow, look-up the ‘new’ reactance value as per the profiles in Figure 2. Enter that value as the new reactance for the pmFCL model, while keeping the RCU value constant.
4) Repeat (2) and (3) until the change in pmFCL reactance between two steps is less than 1% of the previous value. This is typically achieved after 3-4 iterations.

The above manual iterative process can be used for any type of power system analysis package, alternatively scripts have been developed to reduce the analysis time.

**VisSim PC simulator**

FaultCurrent Ltd has also produced a PC based simulation tool that helps to demonstrate the electrical performance of the pmFCL based on a loop current flowing from the source transformer with its internal impedance components, through the pmFCL and into an inductive power factor load. The pmFCL 5MVA to 20MVA variants are accommodated by series parallel combinations of winding configurations. The tool was programmed on the VisSim software package.

Input parameters and variables within the tool allows the user to:

- input parameters for the network upstream of the pmFCL ($R_{source}$ and $X_{source}$)
- input parameters for the load ($R_{Load}$ and $X_{Load}$) downstream of the pmFCL
- determine the time of fault occurrence and fault clearance
- define the resistance ($R_{fcl}$) of the pmFCL
- simulate different fault types including three-phase faults
• select the desired version of the pmFCL (20MVA, 10MVA or 5MVA)

• for comparison, simulate scenarios without a pmFCL or with a CLR instead (the user can define the inductance of the CLR)

The self-inductance ($L_{\text{fcl}}$) of the pmFCL is variable and current-dependent and is taken from look-up tables that were created through finite element analysis (FEA) of the device. The FEA also demonstrated that mutual inductance between the phases is very small and can be ignored.

**Outputs and results**

The tool generates graphs of the phase currents pre-fault, during the fault and post-fault and so it allows the user to see the reduction in fault current that the pmFCL can offer at different times. The tool also produces graphs showing the voltage across the pmFCL resistance and inductance.
Case Studies

Through use of the simulation tool, the white paper demonstrates below two possible applications of the 20MVA pmFCL.

*Bus-section application at 33/11kV Primary substation – Case Study 1*

![Figure 4: Bus-section application of 20MVA pmFCL](image)

The figure above (Figure 4) shows a Primary substation without a fault current limiting device that has reached its fault level limit (a) and the same Primary substation with a bus-section application of the 20MVA pmFCL (b).

The fault is considered to occur electrically close to the 11kV busbar. The upstream network was considered to be infinite, i.e. presents zero impedance during the fault.

In a well-designed Primary substation during normal operation the downstream load is supplied equally through the two transformers (T1 and T2), which are consequently only half loaded (10MVA). There is no current flowing through the bus-section and hence there are no losses or voltage drop associated with the pmFCL.

The reduction of the prospective fault current at the fault location due to the 20MVA pmFCL is tabulated below:
Table 3: Case study 1 results

<table>
<thead>
<tr>
<th></th>
<th>No pmFCL</th>
<th>20MVA pmFCL</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak asymmetrical fault current</td>
<td>34.4kA</td>
<td>29.46kA</td>
<td><strong>4.94kA (14.4%)</strong></td>
</tr>
<tr>
<td>Symmetrical RMS fault current</td>
<td>13.1kA</td>
<td>11.02kA</td>
<td><strong>2.08kA (15.9%)</strong></td>
</tr>
</tbody>
</table>

Looking only at the reduction to the fault current that is associated with the pmFCL, i.e. the fault current through T2 and the fault current contributed by the fault infeed on the right, the reduction that the pmFCL offers is **31.8%** to the RMS symmetrical and **28.2%** to the peak asymmetrical fault current.

The fault current flowing through the 20MVA pmFCL, as shown in Figure 4 from right to left, for a fault between 0.4sec and 0.5sec is shown below (Figure 5).

![Figure 5: Fault current through the 20MVA pmFCL – Case Study 1](image_url)
Case study 2 (Figure 6) below considers a 20MVA pmFCL on the leg of a 33/11kV transformer (b) and compares it to a similar application of a 20MVA CLR (c). The unrestricted scenario is also pictured (a).

![Figure 6: Transformer application of a 20MVA pmFCL and comparison with a CLR](image)

The same assumptions as in Case Study 1 were considered here too (i.e. fault location and its impedance, well-balanced Primary). The CLR was appropriately sized to offer the same reduction to the peak asymmetrical fault current as the 20MVA pmFCL.

In terms of fault current limitation at the fault location, Table 4 summarises the results:

### Table 4: Case study 2 results

<table>
<thead>
<tr>
<th></th>
<th>No pmFCL</th>
<th>20MVA pmFCL</th>
<th>Reduction</th>
<th>CLR</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak asymmetrical fault current</td>
<td>34.4kA</td>
<td>30.67kA</td>
<td>3.73kA (10.8%)</td>
<td>30.67kA</td>
<td>3.73kA (10.8%)</td>
</tr>
<tr>
<td>Symmetrical RMS fault current</td>
<td>13.1kA</td>
<td>11.61kA</td>
<td>1.49kA (11.4%)</td>
<td>11.78kA</td>
<td>1.32kA (10.1%)</td>
</tr>
</tbody>
</table>

In isolation, the pmFCL could reduce the fault current flowing through T2 from 5.25kA RMS / 13.75kA peak to 3.76kA RMS / 10.12kA peak offering a reduction of **28.4% / 26.4%**. As mentioned before, the CLR was sized to achieve 26.4% too. However, the RMS symmetrical fault reduction of the CLR was calculated to be lower than that of the pmFCL (25.1%).
The main disadvantages of the CLR could be observed under normal system operation. The CLR was assumed to have a resistance of 0.66% on rating (0.0403Ω) and chosen to have a reactance of 6.6% on rating (0.403Ω) to give the required reduction for the comparison, while the pmFCL under normal conditions would present a much lower impedance of 0.18 Ω. This equates to a power transfer advantage of the pmFCL over the CLR of approximately 240KW in to a lower power factor load.

This impedance of the CLR could alter the sharing of power flow between the two transformers of the Primary substation and cause voltage control problems. This could lead to increased real power losses. In general, the higher the impedance that is inserted in series with one of the transformers, the higher the possibility for the above issues to arise under normal operation.

The current flowing through the 20MVA pmFCL with a fault between 0.4sec and 0.5sec is shown below (Figure 7).

![Figure 7: Current through the 20MVA pmFCL – Case Study 2](image-url)
Future Work

The pmFCL variants that were considered so far are 2-port configurations that can be installed in series in 11kV systems. However, due to the pmFCL’s flexible nature, it is possible to consider a 3-port pmFCL device that could be connected in series with the bus-section at a substation, like the 2-port pmFCL, but with an additional mid-point winding connection for a transformer (Figure 8). This arrangement of pmFCL elements can also be extended to multiple complete pmFCLs to increase the load flow currents if required.

![Figure 8: 3-port pmFCL (per-phase view)](image)

Further work will be undertaken to study in detail the 3-port configuration, which might have application in substations with three parallel transformers.

Conclusion

The pmFCL device offers many significant advantages and can be a key smart solution to the problem of providing additional fault level headroom in numerous Primary Substations across the UK, thus facilitating the connection of additional DG or demand through reconfiguration and helping the UK to meet its carbon reduction obligations.
Appendices

Appendix A – Case Studies

The following parameters were considered for the case studies:

<table>
<thead>
<tr>
<th>Table 5: Case studies parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 &amp; T2 (33/11kV)</td>
</tr>
<tr>
<td>Rating</td>
</tr>
<tr>
<td>20MVA</td>
</tr>
</tbody>
</table>

* per unit values based on 100MVA and 11kV

For Case Study 2, the 11kV 20MVA CLR was sized to have an impedance of 0.04033+j0.4033Ω (0.066+j0.666pu on rating).

The pmFCL performance during a fault was simulated with the pmFCL tool.

The following parameters were input into the tool:

- 1-ph RMS system voltage: 6.35kV
- System frequency: 50Hz
- Positive sequence ABC (phases 120° degrees apart)
- Symmetrical 3-ph fault with fault impedance of 0Ω
- Time of fault occurrence: 0.4sec (20 cycles)
- Time of fault clearance: 0.5sec (25cycles) (100msec after fault occurrence)
- 20MVA pmFCL: per phase parameters ➢ Number of branches: 4
  ➢ Number of coil turns on limb: 46
  ➢ Resistance: 0.003615Ω
  ➢ Inductance: as taken from look-up tables created from finite element analysis
Appendix B – References


