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Protection issues in the presence of power electronic converters in smart LV residential networks

Arash Amiri | **Andrew M. Cross**

Centre for Renewable Energy Systems Technology (CREST), Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, UK

Correspondence
Arash Amiri, Centre for Renewable Energy Systems Technology (CREST), Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, LE11 3TU, UK.
Email: a.amiri2@lboro.ac.uk

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Abstract
The use of a power electronic converter to step-down the voltage at the point of connection to individual residential houses is being considered in the UK. This is so that the voltage on the existing low voltage cables can be boosted, which would result in an increase in capacity without the need for costly reinforcement. This capacity increase is needed to accommodate an anticipated take-up of new, low-carbon technologies such as electric vehicles and electro-heat. The inclusion of a power converter and communications device also offers the opportunity for smart-grid functions such as managing local demand through voltage control. This study considers the design of this converter within the context of wiring regulations and standards that currently apply to a residential property. In particular, it is found that the rating of the converter is determined by the need to co-ordinate with the existing circuit breaker protection within the house. A protection strategy is therefore proposed for the converter, which is evaluated using a statistical simulation study.

1 | INTRODUCTION

A key challenge facing the distribution network operators (DNOs) today is the increasing demand for power being placed on residential low voltage (LV) networks, for example by the proliferation of electrical vehicle (EV) charging and the move to electro-heat [1–8]. Also, the increase in distributed generation (DG) such as roof-mounted photovoltaic panels (PV) is resulting in unacceptable voltage rises within the LV network. This rise is caused by PV generation from houses at the end of a line, producing a large voltage increase across the feeder impedance at properties close to the substation [9–11]. The current solution to both these problems is to replace the existing conductors—which in the UK are primarily underground—with higher rated, lower resistance cables, this is termed reinforcement. The re-laying of cables is both costly and very disruptive to local businesses and the general public.

Work carried out in the UK [12–14] showed that a more cost-effective solution to reinforcement, is to increase the local, nominal network phase voltage from 230 V to a maximum of 346 V—the existing cables are rated at 600 V. A DNO-owned device is then needed to step the voltage back down to 230 V at each house. The only viable location for this unit is within the electricity meter-box of each property. The size of the meter-box prevents the use of a line-frequency transformer, but the study concluded that a low-cost, high-efficiency power electronic converter (PEC) could be a feasible alternative. The higher power density of the PEC being achieved using new, wide-bandgap power transistors. Such an increase in the local network voltage would therefore (i) provide a higher power throughput on the existing cables and (ii) the use of a PEC with closed-loop control would allow a tight regulation of the voltage at a property, which would mitigate DG induced voltage rises on the network.

The use of a PEC, which inherently contains a microcontroller and sensors, also offers the opportunity to provide additional "smart" functions, in particular the control of load at a single property or group of houses, smart metering and by fitting communications a wide area monitoring capability. Depending on the PEC topology, it can also provide reactive power control, harmonic compensation [4] and a direct DC charging connection to EVs as well as selective fast charging amongst a number of houses [14].

Work is now underway, which is looking at designing and building a number of 23 kVA Gallium Nitride (GaN)-based PECs, which will be tested on the UK, LV network [15,16]. The PEC must comply with existing wiring regulations/standards for domestic properties, which are primarily concerned with the protection of installations and personnel, such as protection against fire and electric shock. In addition, these regulations also include power quality specifications, for example maximum and minimum supply voltage levels. This study looks at the implications of these requirements on the design of the PEC. In particular, it is found that because of the limited overload capability of the PEC, which is constrained by the rating of the power electronic transistors, heatsink and passive component ratings, it can only supply a limited fault-current [16]. Co-ordination of the PEC with existing circuit-breaker/fuse protection within the house is therefore a significant issue.

Similar work has been carried out, for example for the protection of so-called microgrids, which are also constrained by the ratings PECs. Various studies have been reported in the literature and a number of solutions have been proposed to tackle these challenges [17–21]. However, these studies are concerned with the protection of the network itself and not the end users; the key-difference being the requirement for shock protection for the end user and hence the need for wiring regulations.

Whilst many of the general, theoretical concepts behind the development of wiring regulations and standards may be well known to power systems engineers, the area is not familiar with power electronic designers. Research into the integration of power electronics into a residential environment is not very common. A literature survey identified only one reference as being similar to the PEC application. This reference discussed German safety standards for the integration of domestic photovoltaics [22]. To embark on the design of a PEC product, which would meet existing standards, it was concluded that an additional study would be needed to try and identify the rationale behind the current regulations. This was made difficult by the fact that the science that underpins a regulation is not usually available. In addition, what information there is may be spread across a number of non-standard sources, such as institutional or trade magazines and forums. This study therefore contains a summary of this study, which looks at existing regulations/standards that apply to domestic customers on LV networks and the main criteria that would affect a generic PEC design. These criteria are then applied to the PEC that is being developed for a UK project [14–16], within the context of the UK wiring regulations and standards. A key aim of this study was that the PEC design must not entail any changes to the existing wiring regulations. Otherwise, failure to get such changes approved, or an excessive length of time needed to gain approval would pose significant risks to the project.

A protection strategy is then proposed for both the PEC and the existing house protection, which ensures correct co-ordination between the two. This strategy is investigated and further refined using a Monte-Carlo based fault study of the house wiring and loads, which allows the PEC overload characteristics and circuit-breaker/fuse settings to be defined.

Whilst the results of the study apply to the UK LV networks, the methods and conclusions are equally valid for power systems in other countries worldwide. In addition, the results can also be considered for other future domestic applications where the primary power source to a property passes through a PEC, for example an islanded house fed from rooftop PV, so called Solar Homes [23].

2 | NETWORK CAPACITY INCREASE BY ADJUSTING THE LOCAL VOLTAGE

An industrial consortium representing the complete supply-chain from DNO end-user to power transistor device manufacturer, recently investigated the feasibility of increasing the UK residential network voltage to provide a corresponding increase in capacity [16]. This was motivated by the need to meet the needs of increasing demand from EV charging and a move to electric heating in homes. Increasing the voltage was seen as a more cost-effective solution to uprating the existing underground cables [14].

The idea arose from the DNO noting that during normal operation, the existing cables were underutilised in terms of voltage, having a phase-voltage rating of 600 V, which is well above the nominal operating voltage of 230 V. This gives the opportunity to raise the existing voltage above 230 V. An upper-limit is set by the need to keep the cable within safe limits during a phase-to-ground fault or loss of neutral, where the cable can reach $\sqrt{3}$ times the phase-voltage. A safe voltage would therefore be $600/\sqrt{3} = 346$ V, which keeps the cable voltage within its rated 600 V even during abnormal operation.

An increase in the local network voltage is achieved by replacing the substation transformer. However, a device is then needed at each house to step the voltage back down to 230 V. Further studies showed that this device would need to have a maximum rating of 23 kW, Section 3.3 of [24], and be located within the electricity meter-box of the property. This precludes a line-frequency transformer and therefore a PEC was chosen (see Figure 1).

The choice of PEC circuit topology is restricted by the need for a continuous neutral within the converter circuit—this is discussed, in more detail, in Section 5. The most suitable topology was found to be the so-called AC Chopper, shown in Figure 2, also as known as a single-phase matrix converter [25].

The power electronic circuit shown in Figure 2 consists of four power transistors, the upper and lower pair: S_1/S_2 and S_3/S_4, forming two, four-quadrant, bidirectional switches. The principle of operation of the converter is identical to that of the DC-buck converter, where the input voltage is chopped at high frequency and then filtered through the passive LC filter components L_{out} and C_{out}. The duty cycle of the chopped waveform is used to adjust the magnitude of the 230 V sinusoidal output. Closed-loop feedback control is implemented to maintain a tightly regulated output voltage through voltage transducer VT_o, in response to changes in the input network voltage and output load. The converter requires a current-limit function to limit fault and overload currents. This is explained in Section 5 and necessitates the current transducer CT. An important control issue encountered with the AC chopper circuit is the need to adjust the commutation sequence of the

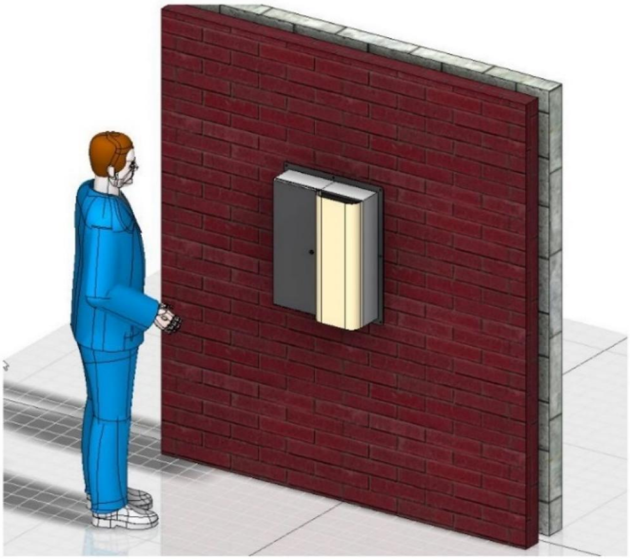

FIGURE 1 PEC mounted in the meter box of a domestic property

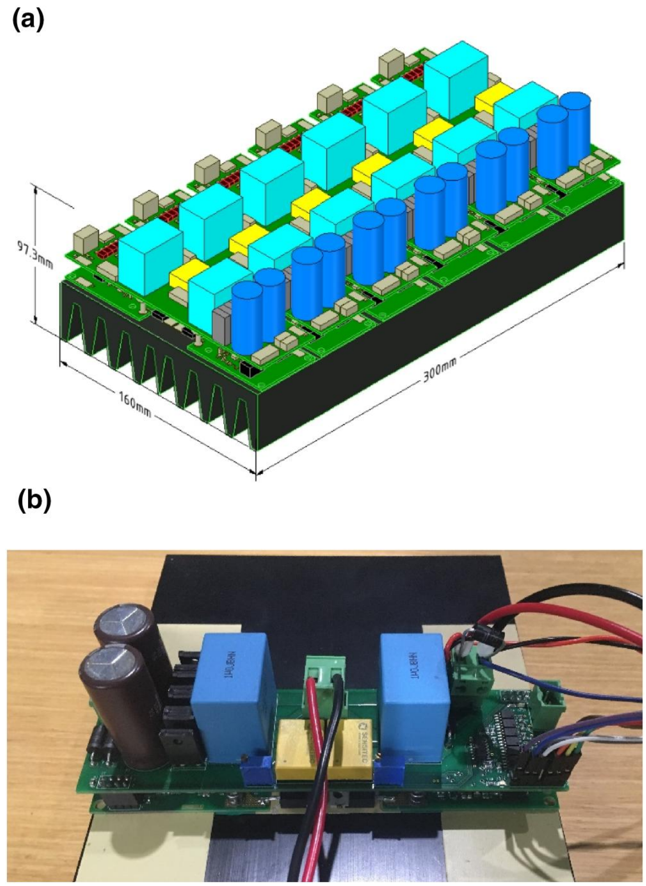

FIGURE 3 (a) Modular 23 kW, GaN based PEC: general arrangement and (b) a 2.5 kW prototype module; having a 250-kHz switching frequency

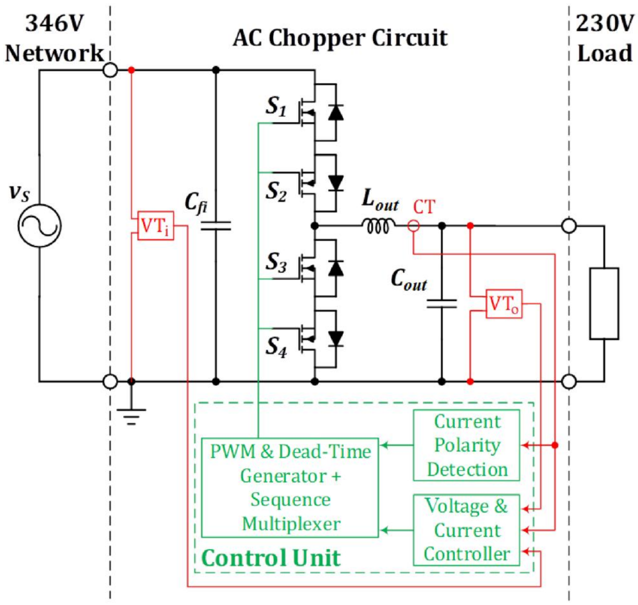

FIGURE 2 Four-switch AC Chopper circuit

switches as the supply voltage changes polarity. This requires an additional voltage transducer VT_i to detect the input voltage polarity, which is used to control the PWM and dead time sequencing logic. An alternative method uses the polarity of the output current fed from the current transducer CT, or a more robust function uses both input voltage and output current polarity [25].

A prototype of the converter, which is based on the multi-module design shown in Figure 3(a), has been built and tested. A prototype of one of the modules, rated at 2.5 kW and utilising new wide-bandgap GaN transistors, having a switching frequency of 250 kHz is shown in Figure 3(b). The GaN transistors allow very high switching frequencies to be achieved, which results in a highly power dense design. A power rating of 23 kW was chosen as being representative of a home with electric cooking, heating, shower and slow to fast EV charging.

The connection of the PEC is between the existing DNO fuse and the electricity meter, as shown in Figure 4. Separate metering is required if EV charging is connected to the 346 V side; however, this option was opposed by the DNO on commercial grounds.

The use of a PEC also gives the opportunity to tightly regulate the nominal 230 V at the house using closed-loop voltage control within the PEC power electronics. This then allows a much wider variation of voltage on the network and helps overcome the voltage rise problems that are being encountered with embedded DG. The technology would therefore help remove one of the barriers to increased deployment of DG such as photovoltaics.

Since the PEC contains a micro-controller and sensors, then with the addition of a communications device it can perform some of the functions proposed for the Smart Grid. Assuming some hierarchical controller, these can include:

i. Moderate control of load demand: This can be achieved by adjusting the PEC output voltage within restricted limits.

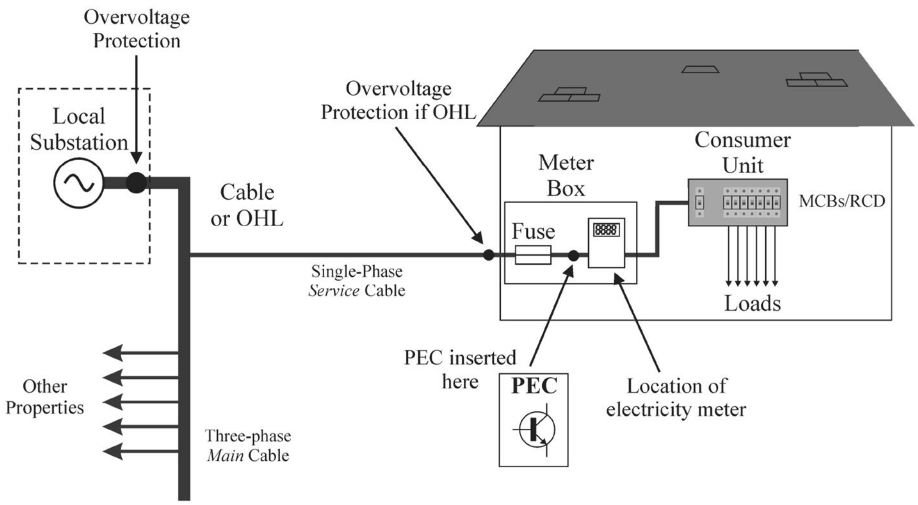

FIGURE 4 Proposed location of the PEC within a house in relation to the existing protection devices

ii. Management of fast EV charging: A dedicated EV AC or DC charging port on the PEC would be either enabled or disabled depending on the total load on the local network.

The work concluded that an important obstacle that would need to be overcome before the deployment of the PEC would be the requirement to comply with existing wiring regulations and standards. Importantly the PEC would need to co-ordinate with the existing protection within the house.

3 | WIRING REGULATION AND STANDARDS

The safe operation of an electrical installation is governed by a number of general concepts. But differences in the design and configuration of different networks as well as the expected degrees of safety have led to different standards being developed worldwide. The UK has one of the strictest regulations in electrical safety, covered by British Standard BS 7671—"IET Wiring Regulation, Requirements for Electrical Installations" [26].

Common objectives of protection outlined in these regulations for domestic environments are:

- Electric shock: Prevention of death or injury.
- Overcurrent: Avoidance of fire, hazardous discharge or blinding arcs.
- Temperature rise: Prevention of burns to individuals through touch or damage to the installation or equipment.
- Overvoltage and electromagnetic compatibility (EMC): To restrict excessive voltages that may cause equipment failure or damage to the installation.
- Proper functioning: For example, the installation must ensure that the supply voltage is within a certain tolerance so that equipment will operate within safe limits.

The protective methods that are used to implement these functions are:

- The insulation, enclosure or the use of physical barriers to live, conductive parts of the installation: This will protect against electric shock.
- Equipotential bonding: Will ensure that if contact with a live part occurs, an excessive potential difference will not be applied across any part of a person's body.
- Automatic disconnection of the supply (ADS): This will protect against overcurrents, and limit temperature rises. This includes the use of fuses, miniature circuit breakers (MCBs). Whilst these devices also give some protection against electric shock, a more reliable method is to use a so-called residual current device (RCD) circuit breaker.
- Voltage regulation: The upstream power system is designed to ensure that the supply voltage falls within certain limits. This method also includes overvoltage/lightning protection.

The installation of a PEC at a property must ensure that these existing protection functions are not compromised and ideally, that these functions are enhanced.

4 | REVIEW OF PROTECTION IN RESIDENTIAL NETWORKS

4.1 | Overcurrent and overvoltage protection

Referring to Figure 4, the local substation contains fuses to protect the outgoing, three-phase conductor from overcurrents. The term *overcurrent* corresponds to either a short-circuit fault or an overload. The three-phase conductor in Figure 4 is called the *Main* cable but might also be an overhead line (OHL). Lower rated single-phase, *Service* cables are used to connect individual properties to the Main cable. These service cables are distributed as evenly as possible across the three phases to balance the load on the Main cable. The service cable, which has a lower rating than the main, is vulnerable to physical damage above ground and short-circuit faults or overloads within the house itself. The service cable is therefore back-protected using a fuse located in the electricity meter-box of the property; this fuse is also shown in Figure 4 and can have ratings which typically vary from 60 to 100 A.

The power system feeding the local substation is designed to provide a regulated supply voltage to the houses. Typically, the voltage will be constrained to a few per cent either side of its nominal value under normal operation, for example 230 V, +10%/–6% in the UK. The substation will also provide protection against overvoltages to the downstream network, which may occur from lightning strikes or system transients arising from the high voltage (HV) supply to the substation. A similar arrangement is used for OHL distribution, but in this case the OHLs are susceptible to lightning strikes and additional overvoltage protection is therefore provided at the incoming supply to a property.

The PEC is located in the meter box and supplies a number of existing MCBs and an RCD, which are located together in what is commonly known in the UK as a Consumer Unit. The Consumer Unit then feeds a number of *Circuits* within the house, the MCBs and cables of each circuit having an appropriate rating depending on its loading, for example lighting: 6 A, electrical sockets: 13 A, cookers, showers and heating appliances: 40 A. Note that the DNO fuse located in the meter box also provides protection to the cables/meter between the meter box and consumer unit. Additional circuits are also starting to become prevalent such as EV charging and PV.

4.2 | Shock protection

Shock-protection in residential networks is necessary due to the supply being grounded at the substation. The term “ground” and “grounding” used here is as defined by the IEEE in [27]. However, the equivalent terms “earth” and “earthing” are used in the UK and these terms are used in this study to mean the same as ground/grounding when referring to a UK network.

The shock hazard resulting from earthing an electrical system is mitigated using so-called basic protection which means insulating all live conductors and/or providing enclosures or barriers. However, if this protection fails, for example through breakdown of the insulation, further so-called fault protection is needed. Examples of fault protection are ADS, double insulation or safety extra-low voltage schemes. An overall electric-shock protection scheme will typically consist of both basic and fault protection and is known in the UK as a protection measure.

One such protection measure, which is also known as ADS, consists of basic protection, using insulation or barriers and fault protection comprising earthing, ADS using a mechanical circuit breaker, equipotential bonding and in some cases additional protection [28,29], such as an RCD. Figure 5

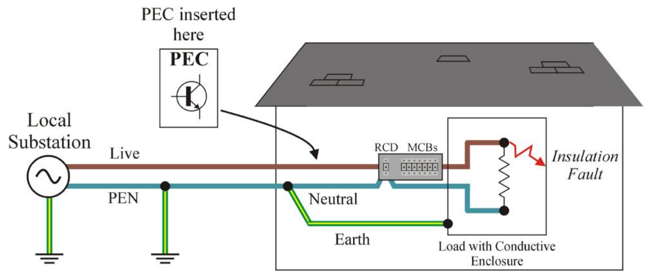

FIGURE 5 Fault protection through automatic disconnection of the supply (ADS)

shows a typical ADS protection measure used in the UK. The phase connection is known as the live conductor. The neutral conductor is grounded at multiple points along its run to the property, which is termed a combined protective earthing and neutral (PEN) conductor [28]. The PEN is split within the electricity meter-box into separate neutral and earth conductors, which are fed into the house. This is commonly referred to as TN-C-S earthing arrangement [26].

The three main components of ADS are:

1. Earthing and ADS: Earthing is used whereby the conductive parts of all electrical equipment which are not normally live—for example the metal enclosure of a domestic appliance such as a coffee-pot/kettle—are connected to the earth conductor. In this way, if the basic insulation protection within the equipment were to fail, such that the enclosure is connected to the live conductor, a fault current would flow from live to earth. This would then trip the MCB in the consumer unit and disconnect the supply—ADS. This then protects against the shock-hazard depicted in Figure 6, where a person has touched the electrical appliance sometime after the fault has occurred, in which case the supply will have already been disconnected. More importantly, protection is also provided if the person is holding the equipment at the instant the fault occurs. This situation is likely to occur with hand-held electrical equipment such as a kettle or clothes iron. In this case a potentially lethal voltage V_{SHOCK} can develop across the impedance of the earth conductor R_{COND}, as a large fault current flows to earth. This shock voltage then appears across the person touching the equipment and their effective resistance to earth R_E. If R_E is small enough the magnitude of the current flow through the body may then exceed safe limits.

The lethality of a shock depends on both the magnitude and duration of current flow [30]. Therefore, in order to safeguard against lethal shock, the upstream MCB must trip within a certain time based on the durations specified in [30]. A typical MCB time/current trip characteristic is shown in Figure 7, and allows for overload and inrush currents as well as short-circuit faults. Overloads are dealt with using a fault-duration-dependent, thermal actuator within the MCB, whereas short circuits are cleared using a fast-acting magnetic actuator.

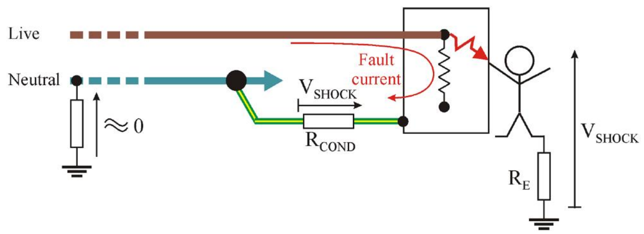

FIGURE 6 Shock hazard in the presence of conductive parts

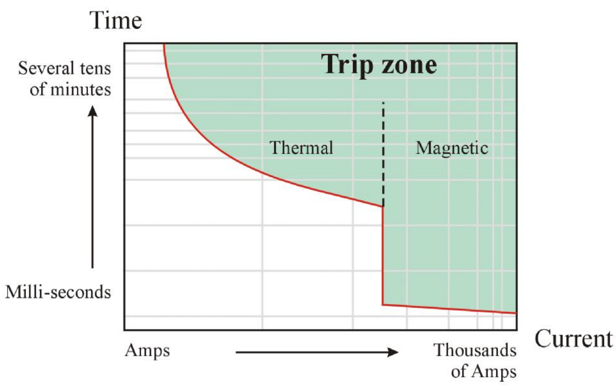

FIGURE 7 Time versus current, trip characteristic of a typical MCB

Figure 7 shows that to minimise the duration and hence lethality of a shock arising from a fault, the MCB must operate in the fast-acting magnetically actuated region. Therefore, the loop impedance as seen by the fault, which includes R_{COND}, must meet minimum values to guarantee the substantial levels of fault current needed to rapidly trip the MCB. There are therefore minimum impedances specified in the wiring regulations for the wiring in a house. In addition, the MCB itself must have a specified maximum trip time when operating in the magnetic actuated region, in order to satisfy disconnection times for shock protection. For example, in the UK, the maximum disconnection time for 230 V AC circuits, with current ratings up to 32 A and with the PEN grounding arrangement shown in Figure 5, is 0.4 s; see Table 41.1 of [26].

2. Additional protection: As well as basic and fault protection, it is also common to include so-called additional protection against electric-shock in the form of a RCD. The RCD is a differential protection device that is fitted in the consumer unit of the property. During a fault to earth, the current flowing in the live and neutral conductors in the consumer unit will become unbalanced. An RCD trips when the magnitude of this differential current exceeds a relatively small, preset value. Therefore, an RCD provides a more sensitive means of detecting faults than an MCB and will typically disconnect the supply in less than 40 ms when the fault current exceeds 150 mA. An RCD is mandatory in the UK on circuits where socket outlets up to 20 A are available, or sockets supplying outdoor equipment up to 32 A; sockets are a particular shock hazard as they commonly supply hand-held equipment.
3. Equipotential bonding: This aspect of ADS is required in order to safeguard against an insulation fault occurring with the presence of a high-impedance earth connection to the property, for example due to an open-circuit PEN fault. This component of ADS does not affect the design of the PEC.

5 | REQUIREMENTS FOR THE PEC TO CONFORM WITH THE EXISTING DOMESTIC PROTECTION

The proposed location of the PEC is within the meter box of a residential property, between the cut-out fuse and the electricity meter as shown in Figure 4. The requirement to be located upstream of the meter is that the DNO owns/operates the network up to this point. In addition, the PEC is located after the fuse, as the fuse provides back-protection to the service cable. The intention in [14] was that the PEC was to be retro-fitted to existing houses, with no change to the internal wiring/protection within the property. In which case, the deployment of the PEC should have no impact on the functioning of the existing protection within a house. The alternative to this strategy would involve a significant modification to the existing standards, which would have major time and cost implications.

The co-ordination of the PEC with the existing regulations/protection therefore raises a number of issues regarding its design. These matters are now discussed in terms of particular requirements within the UK Wiring Regulations [26].

5.1 | Protection against voltage disturbances

With the PEC installed in a house, the existing requirements for the voltage at the input to a property [31,32] now become the voltage requirements for the output of the PEC. The voltage standards that apply to the network then need to be modified to incorporate the maximum substation voltage of 346 V. The voltage regulating function of the PEC now means the limits on voltage excursions on the network side of the PEC can be relaxed, which is of significant benefit to the DNO.

In terms of the Wiring Regulations, important design criteria for the PEC are influenced by:

- Protection against a HV and LV faults, [26] Section 442: (a) HV fault: This is where a short-circuit fault to ground occurring on the HV—normally 11 kV—side of the local sub-station transformer causes an overvoltage transient on the LV side. A maximum allowable overvoltage is specified in Table 44.2 of the regulations, which depends on the duration of the fault. This overvoltage can be as high as 1200 V plus the RMS phase voltage. Additional measures may be needed to ensure this limit is not exceeded, such as minimising the earthing resistance in the substation. For residential networks, it is regarded that this additional protection is provided by the DNO and therefore no further measures are needed for the PEC beyond the need to meet the 1200 V + RMS phase voltage limit. (b) LV fault: Loss of the neutral or short-circuit within a house—similar to (a) above, this can cause insulation stress of up to $\sqrt{3}$ times the phase voltage for an unspecified duration, as stated in Sections 442.3 and 442.5.

- Protection against overvoltages of atmospheric origin or switching, [26] Section 443: Overvoltage transients caused by lightning or circuit switching. Each item of equipment within the house will already be designed to meet minimum impulse withstand voltages, which are typically several kV. Equipment requirements are defined in IEC 60664, which divides equipment into four categories based on their location within an installation and/or availability. The category with the highest voltage is Category IV: 6 kV, which includes the electricity meter. The meter is deemed to be at higher risk due to its proximity to the incoming network supply. Due to its location in the meter-box, the PEC would also be classified as Category IV equipment and would need an input impulse voltage rating of 6 kV with the proposed increased network phase voltage 346 V. Similarly, the PEC design must ensure that its output does not expose the circuits in the house to an impulse of greater than 6 kV.
- Electromagnetic disturbances, [26] Section 444: These standards are for commercial and industrial installations with large numbers of interconnected equipment and therefore they are not applicable to the proposed PEC design. Nonetheless, the PEC itself must satisfy EMC requirements.
- Protection against undervoltage, [26] Section 445: Where a supply undervoltage may cause equipment to operate in a hazardous manner, for example a motor re-starting after an unanticipated restoration of the supply. No values for undervoltage are given in [26], the requirements being that protection measures must be included if a hazard is anticipated. As no additional protection for undervoltage is provided in existing residential properties, then for compliance the PEC output voltage would simply track the supply input voltage if it were to drop below the nominal 230 V. Alternatively, the PEC could provide additional functionality such as voltage step-up, which would maintain the output voltage at 230 V during supply-side dips, but this would require a more complex buck/boost topology. Another option could implement PEC undervoltage lockout when the supply drops below a certain level. The PEC output voltage would then be set to zero until the supply recovered and the PEC manually reset.

5.2 | Electric shock protection

ADS is used for electric shock protection for nearly all installations in the UK and abroad. The key impact of this protection scheme on the design of the PEC is the requirement for a low-impedance connection between the earth and the neutral. This then precludes many traditional power electronic circuits, for example the so-called back-to-back AC/DC converter with sinusoidal pulse-width modulation is shown in Figure 8, which has a discontinuous neutral conductor.

A simple, low-cost, low size/weight circuit, which also has a continuous neutral is the AC chopper shown in Figure 9, which was the chosen candidate for the PEC application [14,25].

With an ADS protection measure, electric-shock protection from insulation failure is primarily through the RCD. However, RCD protection as mandated by the IET Wiring Regulation is an Additional protection measure and therefore it is required that ADS must also be provided through MCB tripping. However, this then places an onerous demand on the PEC design. This is because the PEC then has to supply high-levels of fault current to trip the MCBs. This aspect of electric-shock protection is treated next.

5.3 | Short-circuit and overload protection

Protection needs to be provided in the presence of excessive current flow, which can be due to a short circuit or an overload. A short circuit is designated as a fault and is due for example to an insulation failure or inadvertent connection between live-neutral or earth. On the other hand, an overload is designated as "a flow of current that arises due to a circuit being intentionally or unintentionally loaded above its continuous rating, but where the thermal limits of the circuit have not yet been exceeded" [26]. Inrush currents, which are also a characteristic of domestic loads, can also be categorised as overloads. The duration of an overload must therefore be time-limited, dependent on the magnitude of the overload. Short circuit and overload protection is provided by an MCB having the current/time characteristic shown in Figure 7.

A major problem when incorporating a PEC into a system such as a residential property with MCB protection, is its limited overload capability. Since the PEC must have its own internal thermal protection, it will need to co-ordinate with these existing MCBs in the property. The PEC heatsink/cooling design should ensure its tripping curve lies above that of the MCBs [16] as shown in Figure 10. However, whilst this is achievable in practice, it results in a bulky PEC design, which with a 23 kW rating, cannot fit within the volume constraints of the meter-box.

Overcurrents can also affect the size of the PEC through magnetic saturation of its output inductor—L_{OUT} in Figure 9. Saturation will affect the PEC output voltage regulation control and can lead to excessive voltage distortion, overvoltages and/or PEC instability. In order to prevent saturation, an overrated inductor design is needed, which will then dominate the size/weight of the PEC.

A common solution to the problems of overcurrent capability and inductor saturation is to limit the magnitude of the PEC output current. In this well-used method, the magnitude of the PEC output current is limited by incorporating a current-limit function within the PEC. In current limit

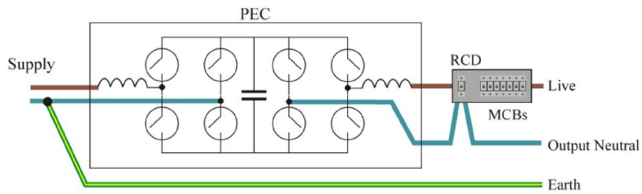

FIGURE 8 Back-to-back AC/DC converter without continuous neutral

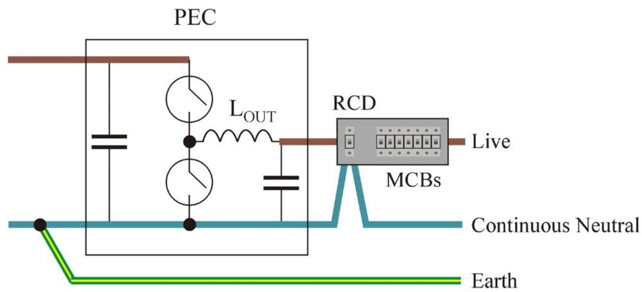

FIGURE 9 AC chopper circuit with continuous neutral

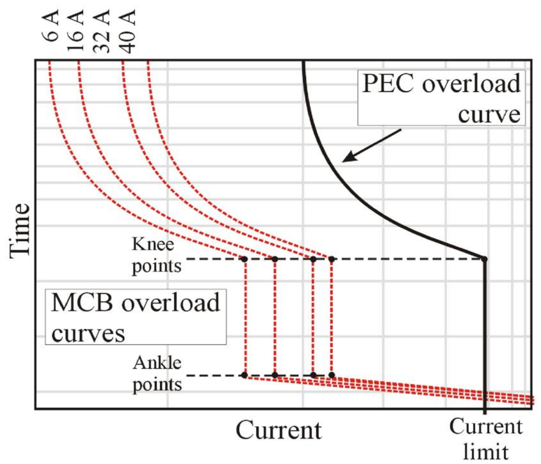

FIGURE 10 Coordination between tripping curves of AC/AC converter and MCBs within the consumer unit

mode the PEC then acts as a current source during the periods of overcurrent, and its output voltage would drop below the nominal 230 V, to maintain the current magnitude. This technique is already implemented in solid state transformers [33] and inverter interfaced renewable energy sources at both transmission and distribution level [34,35]. For the proposed circuit for this application the current limit function can be achieved by incorporating a cycle-by-cycle current-limit function. Another advantage of using such a current-mode control would be the inherent limiting of inrush currents mentioned above. However, since the PEC then acts as a current source during periods of overcurrent, its output voltage would drop below the nominal 230 V, which can cause noticeable maloperation of equipment within the house.

5.4 | Current limit level

Choosing a suitable current-limit threshold for the PEC then becomes a significant design objective. For overloads the selection of the threshold will be a compromise between (1) reducing PEC size and weight and (2) meeting minimum voltage requirements within the house as the supply drops during faults/overloads. In addition, the PEC must provide enough current during overcurrent faults to ensure tripping of MCBs for ADS shock protection. A method for choosing a value for the current limit is described in Section 6.

5.5 | Proposed PEC protection algorithm

A protection algorithm is proposed as shown by the flowchart in Figure 11. This algorithm which runs on the PEC microprocessor, is suitable for the requirements discussed in the previous parts of this section. Normal conditions are defined when the PEC output current I_{out} is below its nominal value, I_{nom}. The PEC then operates in a voltage control mode with a fixed output voltage V_{out} of 230 V. Conversely, when $I_{out} > I_{nom}$, an abnormal condition has arisen and depending on the level of the overcurrent, the PEC goes into either an (i) overload time-tripped mode—still in voltage control mode—or enters (ii) a current control mode with I_{out} restricted by a current limit level of I_{limit}. In the overload time-tripped mode (i) the tripping time, T_{trip}, is set by a pre-programmed I^2t curve which is function of the PEC's thermal design [16].

6 | STATISTICAL STUDY OF OVERLOADS AND SHORT-CIRCUIT FAULTS

To determine the current-limit threshold for the PEC, a MATLAB based computer simulation study was carried out using an electrical circuit model of the wiring in a typical UK domestic property. The study used a Monte-Carlo based circuit simulation to investigate overcurrent scenarios caused by overloads and shocks protected using ADS, which appear as (i) short circuit to earth faults and (ii) overloads between the live and neutral, respectively.

The distinction between a short circuit and an overload used in the study was based on the definition within the regulations for a type-B MCBs: where overloads are those overcurrents which are ≤5× rated current [36]; above this value they are considered as a short circuit.

The overcurrent faults were applied with randomised magnitudes and at with random locations within the property. In addition, the distance of the house from the substation was randomised to take account of differing substation/feeder source impedances. The simulation study assumed worst-case conditions in that the RCD back-up protection had failed, so that the MCBs are providing ADS protection against shock. In

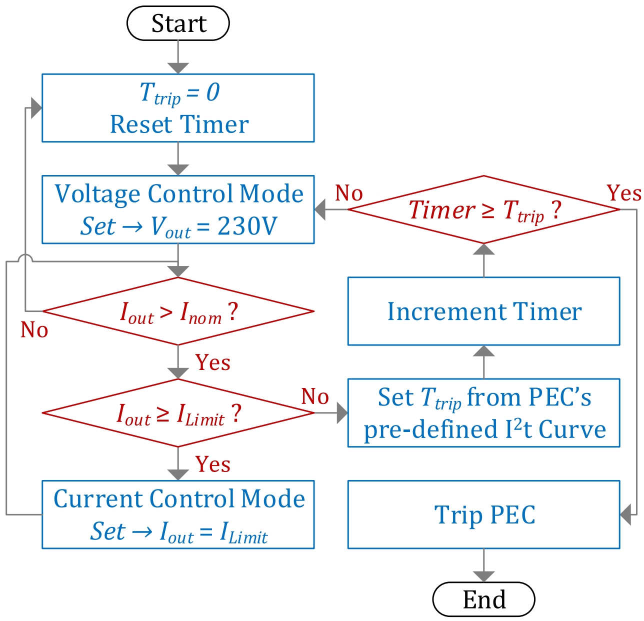

FIGURE 11 PEC internal control and protection algorithm

this case it is vital to ensure that a PEC-fed system would clear faults within a period less than or equal to the existing non-PEC fed house.

The circuit schematic for the simulation is shown in Figure 12 and consists of 10 circuits connected to the consumer unit. These circuits are typical of a modern, 3–4 bedroom residential property with gas-heating: 1 x 6 A single (smoke alarm), 1 x 6 A single (burglar alarm), 1 x 16 A (EV charger) single, 2 x 6 A multiple (up/downstairs lighting), 3 x 32 A ring (up/downstairs and kitchen sockets), 1 x 32 A single (cooker), 1 x 40 A single (shower).

Parameters for the circuit were derived from information within the UK Wiring Regulations [26]. The end-to-end impedance of a circuit connected to the consumer unit Z_c shown in Figure 12, depends on the rating of the circuit, its length within the house and the distance of the house from the substation. This impedance was calculated from the following equation:

$$Z_c = [(Z_s - Z_{s0})x_s + Z_{s0}] - [(Z_e - Z_{e0})x_e + Z_{e0}] \qquad (1)$$

where

x_s: Uniform random variable, 0→1, corresponding to the arbitrary length of a circuit within a house.

Z_s: For short-circuit faults this is the earth loop fault impedance for a particular circuit (Ω)—see Table 41.3 of [26]. For overloads, which flow through the neutral, then the maximum voltage drop specification is used to calculate this impedance.

Z_{s0}: Impedance between the consumer unit and the first load along a circuit (Ω). Assumed to be 10% of circuit length or $(Z_s - Z_e) \times 0.1$.

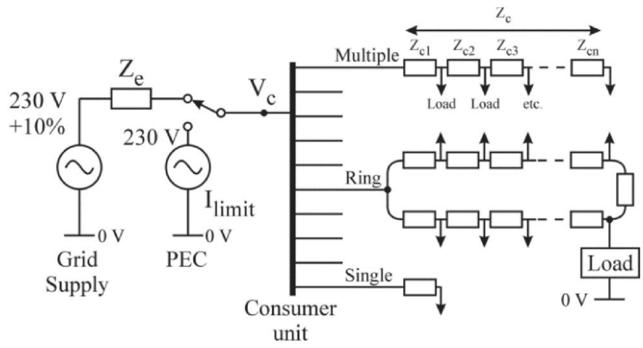

FIGURE 12 Simulation schematic for the installation

x_e: Uniform random variable, 0 → 1, corresponding to the arbitrary distance of a house from the main cable—the length of the service cable.

Z_e: That part of the earth fault loop impedance which is external to the installation = 0.38 Ω maximum from Table 41.4 of [26] for a property fed from a 100 A meter-box fuse.

Z_{e0}: Minimum substation transformer/main-cable impedance = 0.013 Ω from [37].

For circuits with multiple loads including ring mains, the end-to-end impedance Z_c, was then further randomly subdivided into the impedances Z_{c1}, Z_{c2}... Z_{cn}, as a convex combination of Z_c. These impedances correspond to the connection point of each load along a circuit within a house, for example the arbitrary placement of wall sockets.

The calculation of individual loads needs to be obtained for the simulation in order to obtain the pre-loading on the MCBs prior to, and during a fault. The total number of loads on a circuit denoted n, and the load itself was calculated using the Excel based domestic-load forecasting model: "A high-resolution energy demand model" [38,39], developed by the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University. This model generates 24-h, 1-min resolution, active-power profiles for a range of individual domestic loads such as cookers, TVs and other domestic appliances. The electrical loads are calculated using features such as UK irradiance data to predict lighting and a Markov-chain-based building occupancy model, which includes week/weekend and seasonal variations. The calculation also includes stochastic variation of load as well as building occupancy for a maximum of up to one to five residents. The steps used in the MATLAB algorithm to calculate loads from the CREST model were

- The number of non-lighting loads in a 3 or 4 bedroom house is fixed by the CREST simulation as 25, whereas the number of lighting loads is randomly selected between 16 and 38. This corresponds to the fact that most 3–4 bedroom houses have the same type and number of loads.
- A 24-hour load profile was generated for each of the n loads within the house for (i) random days within the year—seasonal variation and (ii) random maximum occupancies—"family" size variation.

- Loads were converted from Watts to an equivalent impedance assuming a nominal 230 V supply.
- 6000 of these profiles were pre-generated as a representative statistical sample and stored in a database. A sample size of 6000 was chosen as this corresponds to $6000/(12\times5) = 100$ samples per month of the year and maximum residency; a value of 100 being a suitably large sample.

A typical relative frequency distribution of the total active-power loading on a property from all 6000 × 24 ×60 samples which is generated by the CREST model is shown in Figure 13.

It can be seen from Figure 13 that the CREST model gives the expected distribution of loading throughout a year in that most load use is for appliances with ratings less than 2 kW, for example TV, computers, kettle and lighting. Whereas higher loads such as 10 kW electric showers are used less frequently.

With loads generated from the CREST model, an overcurrent was then calculated as follows:

- A load profile was chosen at random from the database and the specific load at a random time of the day within the profile was then selected.
- An equivalent overcurrent impedance Z_{OC} (Ω) on one randomly selected circuit was then calculated using the following equations for the short-circuit and overload cases respectively, which assume a 230 V source:

$$Z_{OC} = \frac{230}{5\,I_{MCB}}\,x_f \quad \rightarrow \text{short circuit case} \tag{2}$$

$$Z_{OC} = \left(\frac{230}{1.45\,I_{MCB}} - \frac{230}{5\,I_{MCB}}\right)x_f + \frac{230}{5\,I_{MCB}} \quad \rightarrow \text{overload case} \tag{3}$$

where

x_f: Uniform random variable, 0 → 1, corresponding an arbitrary level of overcurrent impedance.

I_{MCB}: Current rating of the MCB for the circuit on which the fault appears (A).

The constant 1.45 in (3) corresponds to the guaranteed overcurrent level that initiates an MCB trip [36]. The factor of 5 follows from the per-unit, short-circuit trip level for a type-B MCB [36].

- The circuit impedances Z_{c1}, Z_{c2}... Z_{cn}, were calculated from (1) using the random variables x_e, x_s and the random convex combination of Z_c; the value of Z_s being dependent on whether the overcurrent was an overload or a short-circuit.
- The overcurrent impedance Z_{OC} calculated from (2) or (3) was then applied at some random location along the corresponding circuit.

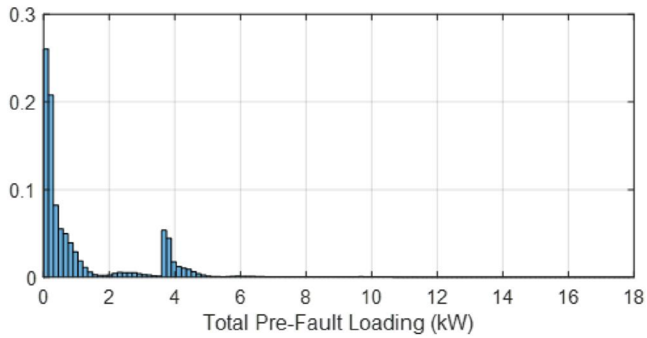

FIGURE 13 Relative frequency distribution of total pre-fault electrical loading on a residential property (kW), calculated from CREST model

- Numerical nodal analysis was then used to solve for the currents in each circuit, as well as the consumer unit node voltage V_c shown in Figure 12. The voltage V_c, represents the effective incoming supply voltage to the house during an overcurrent event and must be checked against minimum requirements. The MCB trip times corresponding to the MCB currents were calculated from standard curves [36].
- The sequence was repeated 1×10^6 times to obtain a representative statistical sample.

In order to assess the behaviour of the protection system and the level of the incoming supply V_c, the 10 branch currents and voltage V_c were calculated at each of the 1×10^6 simulation points for both short-circuit and overload cases. This was carried out for both the PEC and non-PEC cases, the latter being used as a baseline for comparison.

The PEC was assumed to operate with closed-loop voltage control, which incorporates the current-limit I_{limit} for overload and short-circuit conditions. The PEC was therefore modelled as (i) an ideal 230 V voltage source when operating with compliant current-limit and (ii) a current-source when in current-limit. The PEC and non-PEC configurations are represented by the changeover switch in Figure 12. The current-limit was initially set to $I_{limit} = 100$ A and the simulations were then repeated with I_{limit} being incremented in 25 A steps up to 250 A. Since the nominal current rating of the PEC is 23 kW/230 V = 100 A, this gives current limits of 1x → 2.5x.

Initial results from the simulation indicated that the PEC would need to supply an impractical level of current for the majority of the short-circuit events. Whilst the PEC output capacitor can assist in providing short-circuit current, its contribution was neglected since a fault may occur at a zero-crossing of the output voltage. In addition, in practice the value of the output capacitor would be minimised in order to (i) reduce reactive power draw from the supply, (ii) keep the converter size as small as possible and (iii) reduce stability problems associated with the closed-loop voltage control. Therefore, in an attempt to overcome the problem of limited converter output current, the simulations included an additional scenario, where type-Z MCBs were used on circuits ≥32 A. Type-Z MCBs have been specifically developed for use in high-impedance and/or converter fed circuits and have the lowest trip-level of all MCB types; x2.4 → x3.6 [40] compared with type-B x3 → x5 [36].

7 | SIMULATION RESULTS AND DISCUSSION

7.1 | Short-circuit faults

For those faults having a magnitude which classifies them as short-circuit, the simulation showed that when a PEC was fitted there were no un-cleared faults. In addition, there was no loss of discrimination between the PEC and the MCBs in that the PEC's internal protection did not activate.

The majority of the short-circuit faults were found to clear within the required magnetic actuation region of the MCB and could be classified as instant trips. These types of fault have current levels to the right of the knee-points shown in Figure 10. In which case, clearance times are less than the time corresponding to the ankle-points shown on the same curve, which have values of 100 ms, specified in [36,40]. These times therefore fall safely within the required minimum clearance time of 400 ms, for electric-shock protection [26].

However, the remaining faults took greater than 100 ms to clear and were cleared in the slower, thermal region of the curve, which therefore incorrectly classifies them as overloads. For the non-PEC scenario this arises when the total loop-impedance to the substation is too high so that the fault does not generate enough current to instantly trip the MCB, whilst for the PEC case, this misclassification occurs due to the converter current-limit level being below the short-circuit trip level of the MCB. In both these cases, the current levels for these faults lie to the left of the knee points shown in Figure 10 and typically have clearance time of several seconds, for example 12 s for type-B MCBs. This is far in excess of the 0.4 s required for shock protection. In which case, the faults were further checked to see if the shock voltage V_{SHOCK} shown in Figure 6, were above safe levels. A safe voltage level is not defined in the IET regulations, therefore a value of 50 V AC—dry conditions—was taken from IEC and "Safety at Work" documents [41,42]. Those faults that exceed 50 V are shown in Figure 14.

The vertical axis of the figure shows what percentage of faults clear in a time >100 ms, and also have a shock voltage > 50 V. These are shown for the non-PEC case (baseline) and the two PEC cases (i) PEC + type B MCBs and PEC + type Z MCBs—the left-hand horizontal axis; and also as a function of the PEC current limit, which is shown along the remaining horizontal axis. Note that a single bar is used for the non-PEC case as this scenario has no associated current limit.

Figure 14 shows that for the baseline non-PEC network, a small number of residual faults—less than 5%—exceed the 50 V shock voltage level. If a PEC is then fitted with the existing type-B MCBs, the figure shows the number of faults becomes much greater than 5%. This is true regardless of the current limit setting. A type-B-based PEC-based system is therefore worse than the existing network, which would be unacceptable. On the other hand, by utilising type-Z MCBs and using a PEC

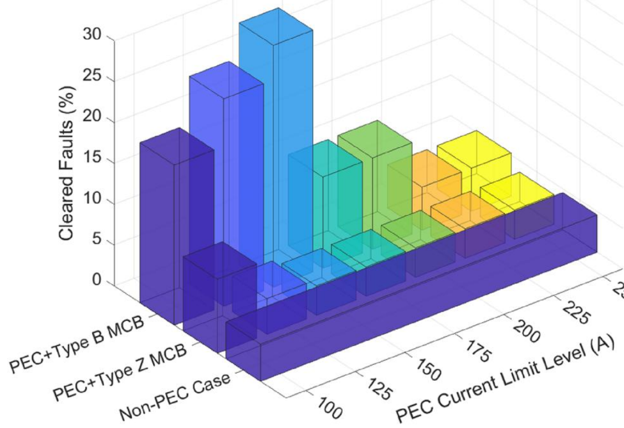

FIGURE 14 Percentage of cleared short-circuit faults that clear in time t > 100 ms and with a shock voltage V_{SHOCK} > 50 V

current-limit of 125 A or higher, Figure 14 shows that the type-Z-based PEC-based system has a lower number of faults than the baseline non-PEC system and therefore provides a higher level of safety.

The next step is to consider those faults that have a safe shock voltage V_{SHOCK} < 50 V, but where the MCB takes a long time to trip. By definition, these faults violate the acceptable minimum voltage supply within the house and can cause maloperation of equipment as discussed in Section 445 of the IET Wiring Regulations. However, the regulations give no quantifiable guide to the transient requirements of an under-voltage, such as its duration. Since these faults may last for several minutes, it is therefore proposed to include a time-dependent undervoltage protection within the PEC to avoid these situations. Alternatively, so-called undervoltage release MCBs are available in the market, which are used to protect sensitive loads. At the moment these devices are relatively expensive due to a limited market. They also have the disadvantage of having a fixed undervoltage threshold. However, a variation on these devices may be an option in the future if MCB manufacturers see the PEC as attractive market opportunity.

7.2 | Overload faults

Again, the simulation showed that there were no un-cleared faults. This means the electrical system within the property is being successfully protected against overloads.

The overload does not require shock protection as the fault current flowing from live to neutral, which has a maximum value of 200 A for a 40 A type-B MCB, results in a voltage V_{SHOCK} of approximately 25 V at the protective earth. A person touching an earthed appliance during a maximum overload is therefore unlikely to suffer any discomfort.

However, similar to the short-circuit case, a problem may arise if long-duration overloads cause significant undervoltage to occur at the property, leading to maloperation of equipment. Therefore, the faults calculated from the overload simulation were assessed for those that violated the minimum supply voltage limit of 230 V—6% = 216 V. These faults are shown in Figure 15.

It can be seen that for current-limits greater than 125 A the PEC-based system produces a negligible number of scenarios that lead to undervoltage when compared with the non-PEC system. This is because the closed-loop control within the PEC ensures a nominal 230 V at the house, whereas the existing non-PEC system is subject to voltage drops along the main and the service cables. Fitting a PEC therefore improves the system in terms of undervoltages.

The results were also searched for faults that caused the PEC to trip before the MCBs, which results in a loss of discrimination. However, no such faults were discovered for the type-Z MCB system, and only 0.004% of faults were found to cause discrimination problems with the type-B MCBs.

8 | CONCLUSION

This study has discussed the issues of the protection of domestic wiring installations when fed from a PEC. A case study consisting of a converter installed in the meter-box of a UK domestic property was considered in terms of the UK, IET Wiring Regulations and its co-ordination with existing RCD/MCB protection within the house.

A key problem was found to be the large output currents that the PEC would need to source during overloads and short-circuit faults within the property, which would lead to a bulky and expensive converter. A current-limit function was therefore been proposed, which is implemented as part of the PEC closed-loop current control. Operation of the PEC whilst in current-limit has two potential issues: (i) an increase in tripping time of the MCBs and (ii) a reduction in voltage to the house. The former issue is of vital importance as it has a direct impact on the protection against electric-shock and fires as mandated in the wiring regulations.

To assess the ability of the PEC to conform to these regulations, a Monte-Carlo based fault study was carried out using circuit simulation. This study showed that circuits of 32 A rating and above within a PEC-fed house, which are normally protected by Type-B MCBs, would fail to meet clearance times for shock-protection. However, this can be overcome by replacing these devices with Type-Z MCBs, which have a lower knee-point, Figure 10, than Type-B, allowing them to have an immediate trip at 3x rather than 5x nominal current. The study found that with Type-Z MCBs, a minimum current-limit of 125 A would be needed. In practice a safety margin would be included, for example 150 A, which equates to an acceptable 50% overload rating for the PEC. Whilst this value of current limit would be suitable to most houses in the UK, in rare cases it may require adjustment where a house has a particularly high load. This would follow existing DNO practice, where the meter-box fuse is uprated for one-off instances of high demand.

Since current-limit is associated with a drop in PEC output voltage, undervoltage tripping can also be incorporated into the converter. This then further improved fault-clearance to better than that of an existing non-PEC system. The PEC-based system, with 150 A current limit would also perform better than a non-PEC system in terms of having fewer overload faults that violate minimum supply voltage requirements: 216 V. This is because the PEC uses closed-loop voltage control, which gives it a lower effective output impedance than the non-PEC system.

The results and conclusions from this study also apply to other domestic scenarios where the main power source feeds the property via a PEC. For example, a PV inverter following islanding through disconnection of the grid supply— so-called Solar Home Systems [23]. Future work on the PEC will consider the new 18th edition of the IET Wiring Regulation, which now includes measures for power supplies with limited fault-current capability, such as PECs. This includes requirements to ensure that during faults, the supply does not exceed 50 V and that additional reinforcement of equipotential bonding is carried out to reduce shock-voltages. In is anticipated that these new requirements will simplify the PEC design.

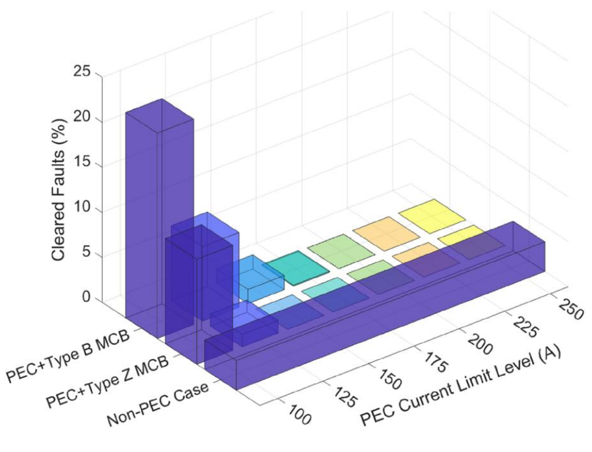

FIGURE 15 Percentage of cleared overload faults that violate the minimum voltage <216 V limit

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ORCID

Arash Amiri https://orcid.org/0000-0003-2040-7230
Andrew M. Cross https://orcid.org/0000-0002-7554-6935

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