Impact of inverter energy systems on fuse protection of low voltage networks

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ABSTRACT

With the introduction of inverter energy systems (IESs) to electricity distribution networks, it is important for electricity distributors to know the nature of new challenges to basic protection systems in the low-voltage (LV) network as the penetration of IESs in distribution networks increases.

For any feeder on a low voltage network hosting IESs, fault currents will have a contribution from both the upstream source and from the IESs connected on that same feeder. The clearing times of upstream fuses can be affected by the additional current contribution from IESs.

It is shown how fuse coordination can be preserved in LV networks with high penetrations of IES, so that cables are still protected. An IES will shut off under fault conditions either because the voltage dips below a threshold, or the upstream fuse clears the fault. Guidelines are presented to help combat sympathetic tripping and blinding of fuse protection systems.

INTRODUCTION

In low-voltage electricity distribution networks, fuses protect cables and overhead lines from carrying excessive current for too long. Fuses are rated to protect the conductor while avoiding blowing under load. Overcurrent in cables and lines may in a short period of time damage the insulation, or the conductor itself, resulting in costly replacement of sections of line. With roof-top photovoltaic Inverter Energy Systems (IESs) becoming more common in low-voltage distribution networks, it is important that fuse protection functions properly to protect downstream conductors in the event of a fault on the line.

Previous studies have identified sympathetic tripping, as a potential problem that can be caused by increased IES penetration [1, 2]. However, they do not provide a clear means of assessing and quantifying the potential for fuse blinding and how to guarantee the protection of conductors when significant IESs are installed on LV feeders. Coffele et al. studied protection blinding in medium voltage (MV) networks in the UK, incorporating distributed generation, and concluded that DG on these networks would not cause protection blinding [3]. It is worthwhile studying the effect of DG on protection in low-voltage networks, particularly since the fault levels in these networks are much lower than in MV networks.

IESs have systems for under-voltage cut-out – activating when the network voltage collapses, and anti-islanding, when the network disappears from the perspective of the IES. There are two thresholds for under-voltage cut-out; 200 V (the prevailing legal requirement in New Zealand according to the Electricity (Safety) Regulations 2010, from AS 4777.3:2005) and 180 V (from AS/NZS 4777.2:2015) [4 – 6]. At the time of writing, inverter energy systems must comply with AS 4777.3:2005 [7]. Clause 7.4 says that if the system voltage goes below 200 volts for longer than a second, then the IES must disconnect within a further one second. This gives a maximum disconnection time of two seconds, while maintaining a minimum trip delay time of one second to allow for brief transients. In the AS/NZS 4777.2:2015, which is yet to be applied in New Zealand, the under-voltage threshold is 180 volts.

When a low-impedance fault occurs in an electricity network, a high current will flow from the source, and the voltage on the line may or may not drop below the threshold at which IESs should disconnect. Since a network may become populated with additional distributed power sources, and since it is the task of the fuse to clear the fault current, there is a possibility of interaction between IES disconnection and LV fuse protection systems. Above the under-voltage disconnection threshold, each IES can be expected to remain connected during a fault, thereby contributing their own fault current to that fault. The amount of current contributed by an inverter is typically around 1.2 times the rated current output [8]. Note that this fault current limitation is not applicable to synchronous machines connected distributed generation systems, which may have significantly higher fault currents.

At the electricity distribution level, protection issues can be categorised into either sympathetic tripping, or protection blinding.

Sympathetic tripping

Sympathetic tripping is the occurrence of unwanted disconnection of generation on healthy feeders, as a consequence of a fault on a nearby feeder. This has three sub-categories:

1.1 When the unwanted disconnection is via a fuse blowing or overcurrent relay operation. This sort of disconnection requires human intervention to restore power, as shown in Figure 1a.
1.2 When there is an unwanted operation of a protection device (i.e. a fuse blowing) downstream of a fault on a feeder. While this does not result in more customers being disconnected, it does make the fault recovery more complicated. This situation is shown in Figure 1b.
1.3 When the disconnection of distributed generation on health feeders is due to abnormal voltage conditions. This type of disconnection is automatically restored when voltage levels return to normal. This sort of disconnection is of little consequence.

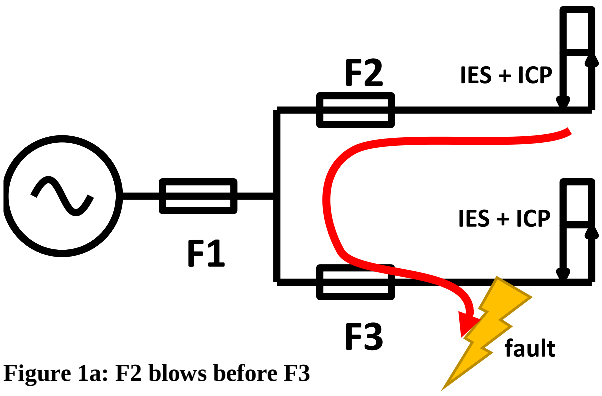

Figure 1a: F2 blows before F3

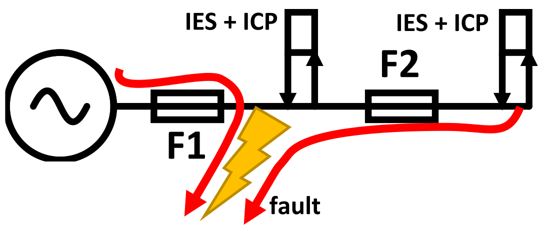

Figure 1b: F2 blows before F1

Sympathetic tripping of types 1.1 and 1.2 require that the affected fuse (F2 in Figures 1a and 1b) blows at the level of fault current that the IES can provide through that fuse (less the current consumed by the ICP loads). Given that this current is just 1.2 times the IES rating, a sensible fuse rating would be higher than this current. This situation is easily avoided by the following recommendation:

Recommendation 1: All fuses should be rated at greater than 1.2 times the combined rating of downstream connected IESs.

Protection blinding

This is defined as when distributed generation on a faulted feeder provides a high enough proportion of the fault current that the appropriate feeder fuse does not clear a fault, when part of the faulted feeder carries a current that could damage the feeder. For this to occur, two conditions must be met. Firstly, the voltage at the IESs on the faulted feeder must remain at or above the minimum voltage threshold (200 or 180 volts), such that they remain connected and contributing to the fault current. Secondly, the current flow at the fault must be high enough that the cable is likely to be damaged. The fault resistance has two bounds – an upper bound above which currents are insufficiently high to damage the cable, and a lower bound, below which IESs disconnect, and do not contribute to the fault current. This situation is illustrated in Figure 2, and determining these bounds is the focus of much of this paper.

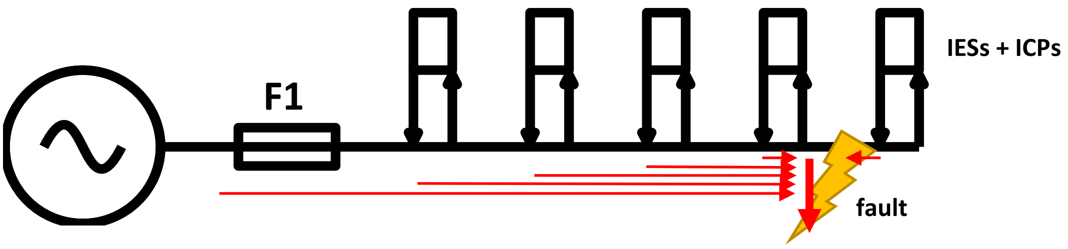

Figure 2: Fuse blinding, where the current through F1 is less than the current through the fault

Fault types

On LV networks, a number of fault types may occur. These may be phase to ground, phase to phase, and 3 phase faults. In general phase to phase and 3 phase faults involves phase conductors making electrical contact with each other, and are low impedance. In contrast, phase to ground faults will often involve a significant fault resistance. Phase to ground faults are addressed first, as they clarify the mechanisms involved, and phase to phase faults are addressed later in the paper.

METHOD

Determination of fault resistance bounds

The aim of this section is to determine, for a realistic LV network, whether a phase to ground fault that should result in a fuse blowing will have voltage levels above the 200 or 180 volt IES disconnection threshold. One single-phase branch of a low-voltage feeder is used to build a model. The model branch is developed from [9], where the originating low-voltage feeder was the “urban” feeder closest to the center of that cluster, otherwise known as “Representative residential LV feeder 1”. The branch is depicted in Figure 3 and its characteristics are summarised in Table 1.

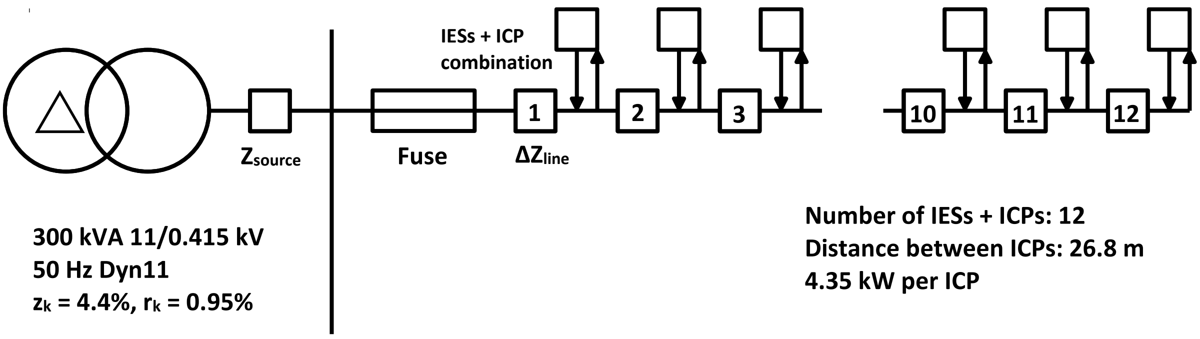

Figure 3: Single phase residential network branch

Table 1: Single-phase residential network branch characteristics

Name	Value	Units
Branch length	322	m
Number of ICPs	12	-
Number of phases	1	-
Maximum line current	265	A
Z_{source}	5.454 + j25.26	mΩ
ΔZ_{line}	14.2 + j14.4	mΩ/ICP
Inverter energy system size	4	kW
IES current contribution	16.67	A/ICP

The transformer characteristics were estimated based on a minimum short-circuit impedance, Z_k, for a rated power between 25 and 630 kVA of 4.0%, and a typical value of percentage resistance, R_k [10]. A Z_k of 4.4%, and an R_k of 0.95% was chosen. From this, the network impedance is determined. Fuse sizes were determined from the conductor's minimum current carrying capacity and a 250 amp DIN class gL Size 2 fuse was selected based on Appendix C of Orion's "Network Fuse Application Guide". The corresponding current-time fusing characteristic was found from an Eaton Bussmann series "Technical Data 10164" datasheet, with part number 250NHG2B [11] [12].

The network feeder can be represented in an electrical circuit, as shown in Figure 4, wherewith the phasor diagram can be drawn, as shown in Figure 5. Because the fault is resistive, the voltage and current at the fault location are in phase.

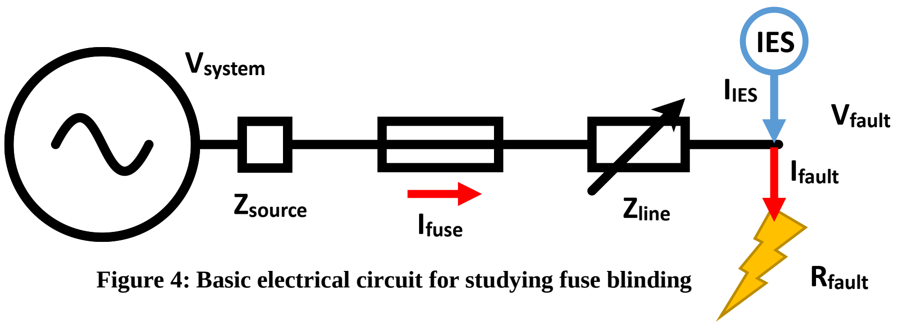

Figure 4: Basic electrical circuit for studying fuse blinding

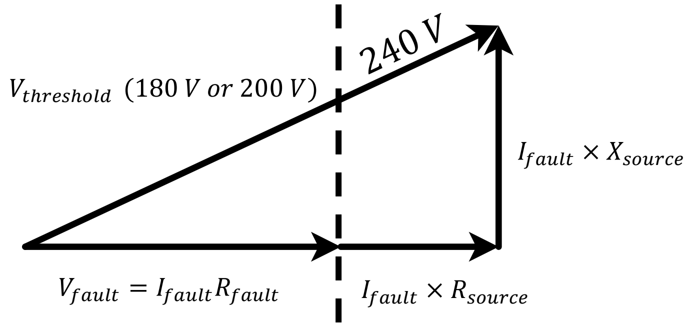

Figure 5: Phasor diagram showing voltage relationships in figure 4

This yields the following equation

$$\left(V_{threshold} + \frac{V_{system}\,R_S(x)}{\sqrt{(R_f + R_S(x))^2 + X_S(x)^2}}\right)^2 + \left(\frac{V_{system}X_S(x)}{\sqrt{(R_f + R_S(x))^2 + X_S(x)^2}}\right)^2 - V_{system}{}^2 = 0 \qquad (1)$$

where $V_{threshold}$ is the inverter under-voltage cut-out threshold, $R_s(x)$ and $X_s(x)$ are the combined system and line resistance and line reactance respectively, and R_f is the resistance of the fault.

It is assumed that in a four-wire, LV network, the neutral size is the same as the phase size, and the phase-neutral impedance is approximately equal to the feeder's positive sequence impedance. Equation 1 is solved for the fault resistance that results in the IES threshold voltage appearing at the fault.

In addition to finding the fault resistance that yields the under-voltage cut-out threshold, a similar calculation can be performed to find the fault resistance where the current drawn is equal to the line current (or fuse current) rating. This is calculated as,

$$R_{fault(I_{fuse\_rating})} = \sqrt{\left(\frac{V_{system}}{I_{fuse\_rating}}\right)^2 - \left(jX_S(x)\right)^2} - R_S(x) \qquad (2)$$

Where I_{fuse_rating} is 250 A, the rating of the fuse. Equation 2 is solved for the fault resistance above which a fuse would not normally blow.

Fuse blinding on a low voltage feeder

A fault located at the last ICP on a low voltage feeder is considered. The fault current will be the sum of the inverter contributions plus the upstream network contribution, as shown in Figure 6. The end of the feeder is chosen, as this location has the maximum number of IESs upstream, and will result in the largest possible line current close to the fault. Thus the part of the line experiencing a potentially damaging current, is upstream of, but close to the fault. This is marked with the orange circle in Figure 6.

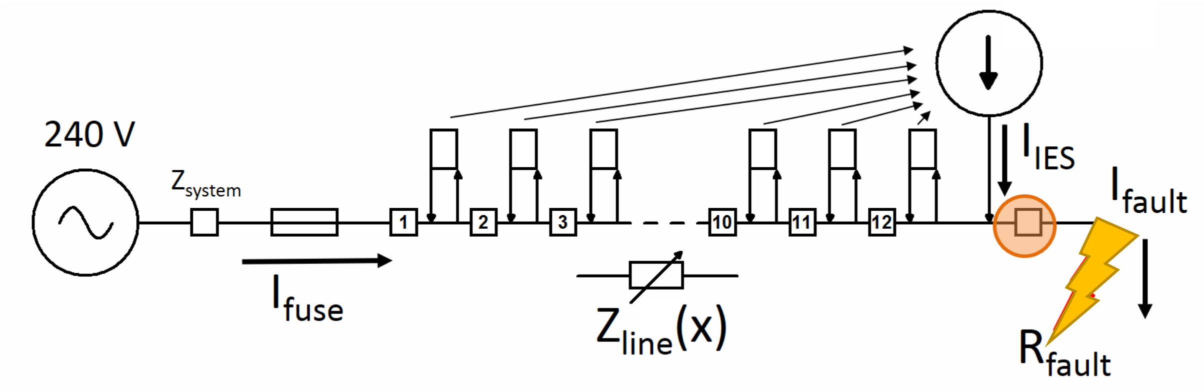

Figure 6: Simplification of protection blinding on the branch by considering a fault at the last ICP

Analysing this circuit gives the following equation 3, which can be solved for I_{fuse}, the current in the fuse, over a range of fault resistances, r = [0..2] Ω,

$$\left(\left(I_{fuse} + I_{IES}\right) \times R_{fault}(r) + I_{fuse} \times R_{source}\right)^2 + \left(I_{fuse} \times X_{source}\right)^2 - 240^2 = 0 \quad (3)$$

Solving this equation, each with total IES current contributions of I_{IES} = 0 A and I_{IES} = 200 A gives the curves shown in Figure 9, which is plotted with the 250 A fuse characteristic obtained from the Eaton Bussmann datasheet mentioned earlier.

RESULTS AND DISCUSSION

Fault resistance feasibility regions

Putting all this together makes it possible to distinguish under what fault conditions the inverters will stay connected, and under what conditions they will trip on under-voltage. Figure 7 is generated from equations (1) and (2), where the blue and red points are the values of the fault resistance that give a voltage of 200 V or 180 V at the location of the fault, while the black points are the values of fault resistance that yield the rated current of the conductor, all with respect to distance along the feeder branch, from the source transformer.

For this example, there is an area in which inverters will remain connected while there is a fault on the feeder, and so these IESs will stay connected and contribute to the fault current. This is depicted by the red shaded region in Figure 8. The region below the 180 V line (blue points), is where IES disconnection can be reasonably expected within two seconds. In this region, the fuse protection should operate normally, if all the inverters on the branch disconnect.

The grey shaded region above the black points is the region in which the fault current is no greater than normal load current, and fuses would not be expected to blow.

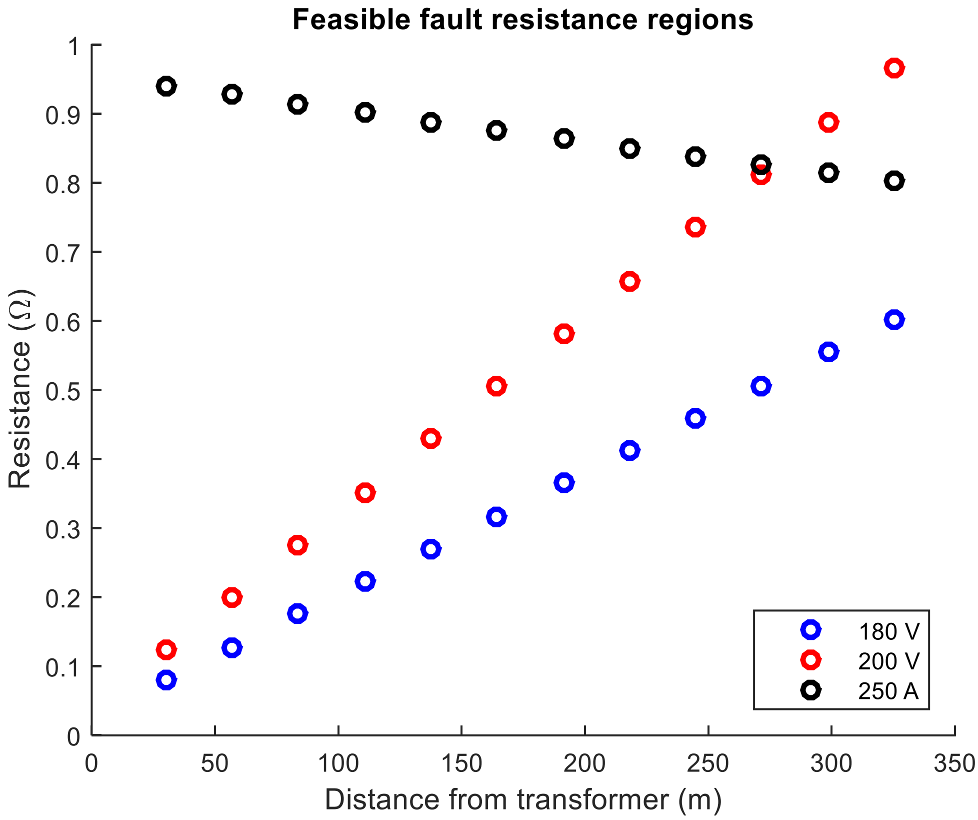

Figure 7: Feasible fault resistance regions

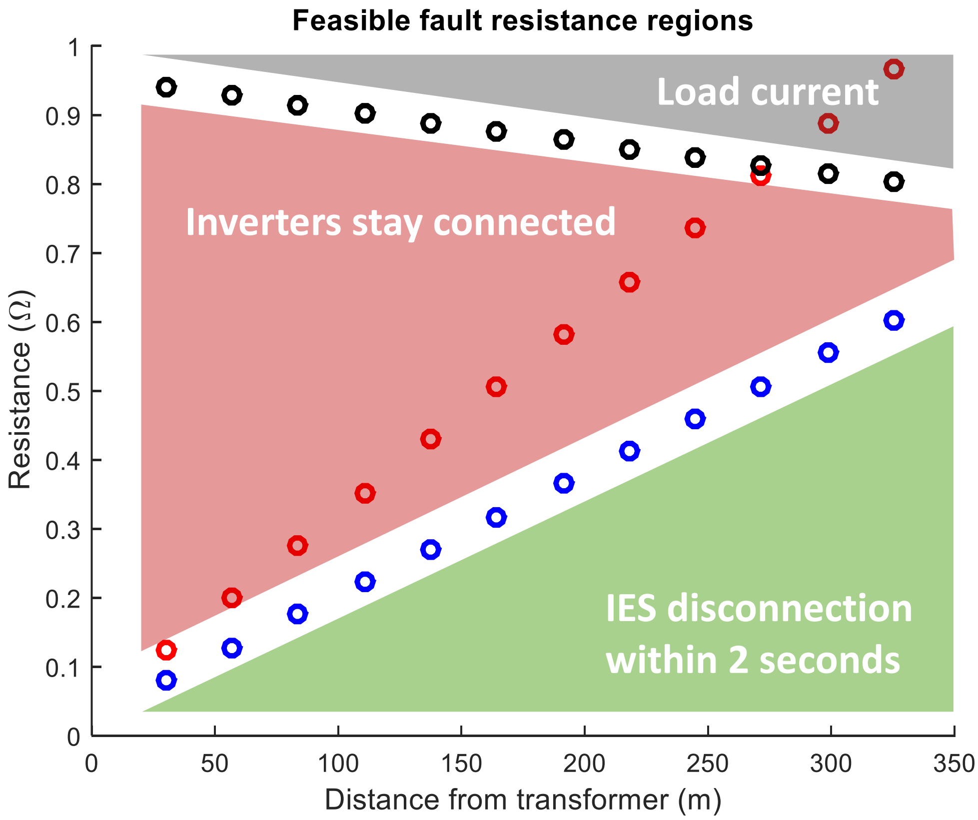

Figure 8: Feasible fault resistance regions with shaded areas depicting inverter behaviour

Fuse protection blinding

Solving equation (3) for the value of current flowing through the fuse, for both zero IES current contribution (blue trace) and 200 A IES current contribution (red trace) allows Figure 10 to be drawn, which plots fuse current versus fault resistance. The figure depicts the situation only at the end of the feeder, so in Figure 8, the relevant problem fault resistance can be found at the end of the feeder branch between the 180 V line and the load current line, or approximately between 0.6 and 0.9 Ω. The black trace is the sum of the current contributions (200 A) from the inverters plus the current flowing in the fuse to give the current flowing in the fault, and therefore the current in the cable section before the fault.

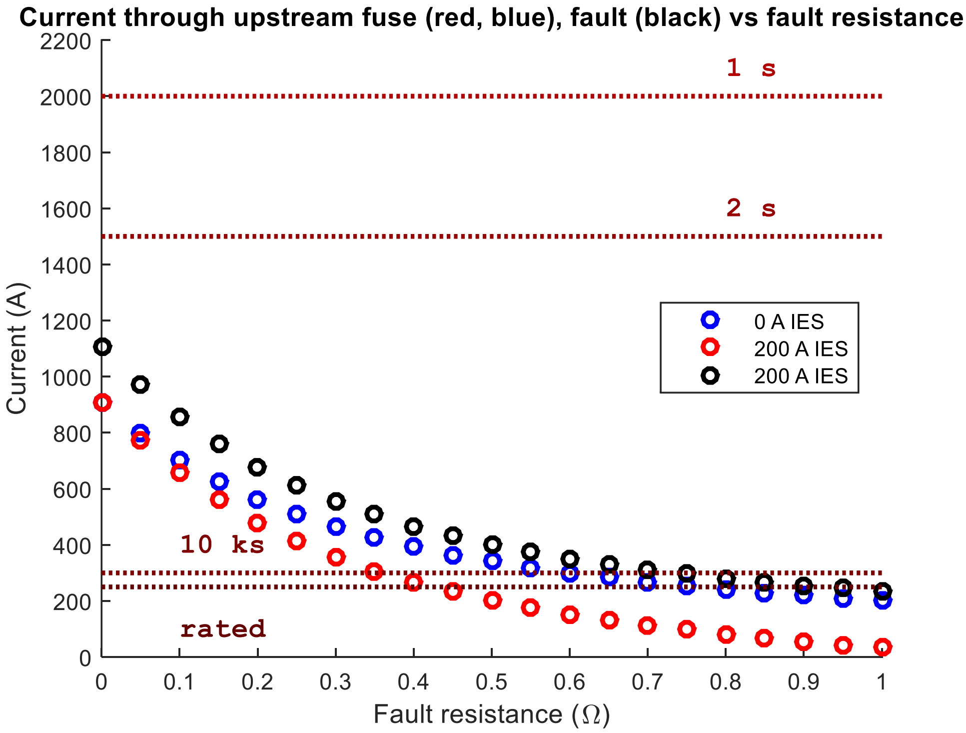

Figure 9: Current through the upstream fuse, and fault, with fusing current superimposed, vs fault resistance

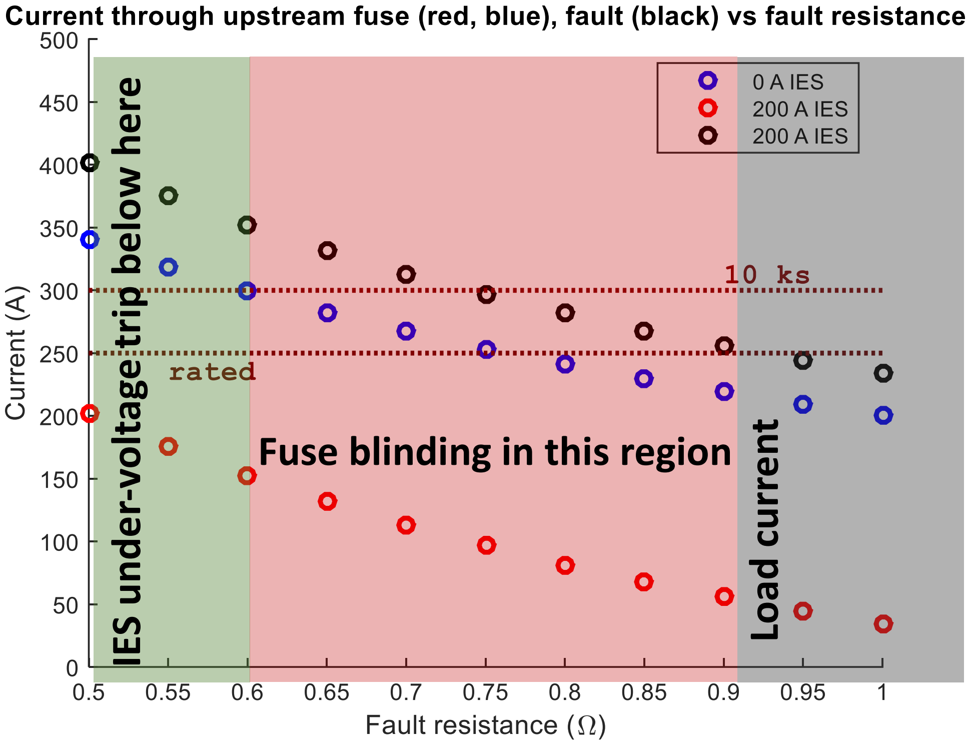

Figure 10: Current through upstream fuse, and fault, with fusing current superimposed, vs fault resistance, close up

Figure 10 zooms in on Figure 9, and shows three distinct regions in which three different behaviours occur. Below the fault resistance found previously (0.6 Ω), the IESs begin to trip on under-voltage (180 V) due to their passive islanding protection. Above around 0.9 Ω, the fault current appears to be no greater than the line rating, and so the cable is in no danger of overheating. However, between these two regions, blinding of the fuse protection is possible. For example, for a fault resistance of 0.7 Ω, the current passing through the fuse (red trace), is 100 A, while the current experienced by the end-section of conductor that feeds the fault is above 300 A. In this instance, the fuse will not act to protect the conductor, and the fault current will continue to pass, until the fault is cleared by some other means, or until load/inverter conditions change on that feeder section.

In summary, for a realistic LV feeder, it is quite possible for line current to be greater than the current experienced by the protective fuse. For this to be avoided, the following recommendation should be followed:

Recommendation 2: It is possible that cable current may exceed fuse rated current by 1.2 times the maximum combined rating of IESs on each particular single phase of that feeder. Therefore fuses should be rated no greater than the cable rating minus 1.2 times the combined IES ratings on the protected feeder.

Phase to phase faults

Phase to phase faults are normally very low impedance, as they result from a direct electrical connection between 2 conductors. They result in a halving of the phase to neutral voltage at the point of the fault, although the reduction is less strong closer to the supply transformer. IES systems close to the supply transformer may remain connected for a fault near the end of a feeder. As per the single phase to ground faults, the fault current could, in this worst case situation, be equal to the fuse current plus the IES fault current contribution. However, Recommendation 2 obviates the chance of cable currents being exceeded without fuse protection operating.

CONCLUSION / PROTECTION GUIDELINES

This paper examines two potential protection problems reported in the literature, applied to a NZ typical LV network. The problem of sympathetic tripping is met with a simple recommendation, that would be met anyway under normal protection setting guidelines.

The problem of protection blinding, where inverter energy systems may contribute to higher line currents than experienced by LV line fusing is investigated, and found to be possible. This problem is also addressed by a simple fuse sizing recommendation, such that cables are still protected from damage. The conclusions reached for single phase to ground faults approximately hold for phase to phase faults, such that the same recommendation is valid.

Both problems require significant IES penetration, and poorly considered fuse sizing. Although there is value in examining other LV networks to test the likelihood of such issues, and further investigation of phase to phase and 3 phase faults would be useful, the recommendations are likely to remain un-altered. This is the subject of future work.

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