Current limiting circuit breakers and cable sizing

Cable damage due to short-circuits are primarily as a result of thermal stress, i.e. overheating of the cable beyond it's maximum short-time temperature limit. For XLPE this is 250°C. The general adiabatic temperature rise equation is:

$$I_F^{\ 2} \cdot t = K^2 \cdot S^2 \qquad \text{(Eq. 1)}$$

I_F = symmetrical three-phase fault current [A]

t = duration of fault [s]

K = constant depending on cable material, initial and final temperature

S = cable area in mm^2

For purposes of this discussion initial temperature is taken as 90°C and final temperature as 250°C (i.e. will use XLPE cable insulation as example).

The $K^2 \cdot S^2$ term is an indication of the thermal capacity of the cable and is denoted by, E. There is an elaborate formula in IEC 60949 detailing the calculation of K. Here we will assume adiabatic heating of the cable under fault conditions (no heat loss to the surrounding).

Also note that Eq 1 is valid for $0.1s \le t \le 5s$. For $t \le 0.1s$ the effect of DC offset in the fault current may not be negligible and so allowance needs to be made for it.

Using Eq.1 the maximum cable withstand current (symmetrical rms) may be determined for a given trip time by making I_F the subject of the formula. This was used to compile Table 1 below. Thus from the table we see that a $50mm^2$ cable can withstand a fault current of up to 10103A for 0.5s.

Also, using Eq. 1 the cable damage withstand curves may be constructed. These are usually a straight line on a log-log scale.

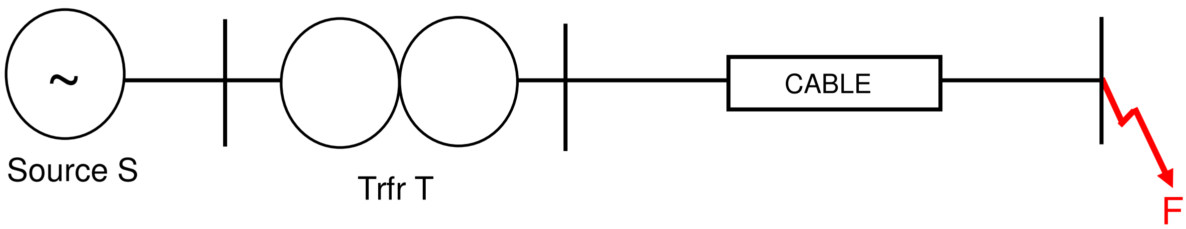
Note – Eq. 1 is applicable to HV as well as LV, 3C or 1C cables.

S [mm^2]	t [s]		
	1	0.5	0.25
1	143	202	286
1.5	214	303	429
2.5	357	505	714
4	571	808	1143
6	857	1212	1714
10	1429	2021	2857
16	2286	3233	4572
25	3572	5051	7144
35	5001	7072	10001
50	7144	10103	14287
70	10001	14144	20002
95	13573	19195	27146
120	17145	24247	34290
150	21431	30308	42862
185	26432	37380	52863
240	34290	48493	68580
300	42862	60616	85724
400	57150	80822	114299
500	71437	101027	142874
630	90011	127294	180021

Table 1 - Copper XLPE/EPR fault current ratings

The minimum cable length conundrum.

Consider the following network:



Suppose the transformer LV network is 380V. What is the minimum length of cable required to ensure that the three-phase fault current at F does not exceed the cable fault current rating for a given time?

In the calculations below, assumed a 500MVA source. Trfr = 1.5MVA. Trip time = 0.2s. For a 2.5mm^2 cable see that the cable must be at least 34m in length. Then the fault current at the end of the cable (790A) is less than the cable withstand rating (799A).

Note that the 799A was calculated from the cable thermal capacity E (i.e. $K^2 \cdot S^2$).

Determining the minimum cable length to ensure fault current is within cable withstand capability

Rated Voltage =	380	V		enter user values
Source =	500	MVA		
Source X/R =	8			
Source Z_S =	0.000289	Ω @	380	V
	0.000035	(complex format)		
Trfr Size [kVA] =	1500	(only 500, 1000, 1250, 1500, 2000 and 2500MVA allowed)		
Z% =	6			
Trfr X/R =	6.54			
Z_T [Ω] =	0.00578			
=	0.0008730	(complex format)		
K =	143			
Maximum fault time [s]	0.2			

	Cable Size [mm²]							
	1	1.5	2.5	4	6	10	16	25
Thermal Capacity, E =	20449	46010	127806.25	327184	736164	2044900	5234944	12780625
Max. Allowable I_F =	320	480	799	1279	1919	3198	5116	7994
Conductor R [Ω/m @40°C]	0.0233	0.0149	0.00814	0.00506	0.00338	0.00201	0.00126	0.000799
Cable length [m] =	**30**	**31**	**34**	**34**	**34**	**34**	**33**	**33**
Cable Z_C [Ω] =	0.699	0.4619	0.27676	0.17204	0.11492	0.06834	0.04158	0.026367
$Z_S + Z_T + Z_C$ =	0.6999088548	0.4628088548	0.2776688548	0.1729488548	0.1158288548	0.0692488548	0.0424888548	0.0272758548
I_F at end of cable [A] =	313	474	790	1268	1892	3156	5113	7856
Cable fault rating exceeded?	No - All Good	No - All Good	No - All Good	No - All Good	No - All Good	No - All Good	No - All Good	No - All Good

Let's suppose the cable length is only 20m for all the cables. Results are now as follows:

	Cable Size [mm²]							
	1	1.5	2.5	4	6	10	16	25
Thermal Capacity, E =	20449	46010	127806.25	327184	736164	2044900	5234944	12780625
Max. Allowable I_F =	320	480	799	1279	1919	3198	5116	7994
Conductor R [Ω/m @40°C]	0.0233	0.0149	0.00814	0.00506	0.00338	0.00201	0.00126	0.000799
Cable length [m] =	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**
Cable Z_C [Ω] =	0.466	0.298	0.1628	0.1012	0.0676	0.0402	0.0252	0.01598
$Z_S + Z_T + Z_C$ =	0.4669088548	0.2989088548	0.1637088548	0.1021088548	0.0685088548	0.0411088548	0.0261088548	0.0168888548
I_F at end of cable [A] =	470	734	1339	2145	3190	5281	8190	12242
Cable fault rating exceeded?	Yes, Bad!	Yes, Bad!	Yes, Bad!	Yes, Bad!	Yes, Bad!	Yes, Bad!	Yes, Bad!	Yes, Bad!

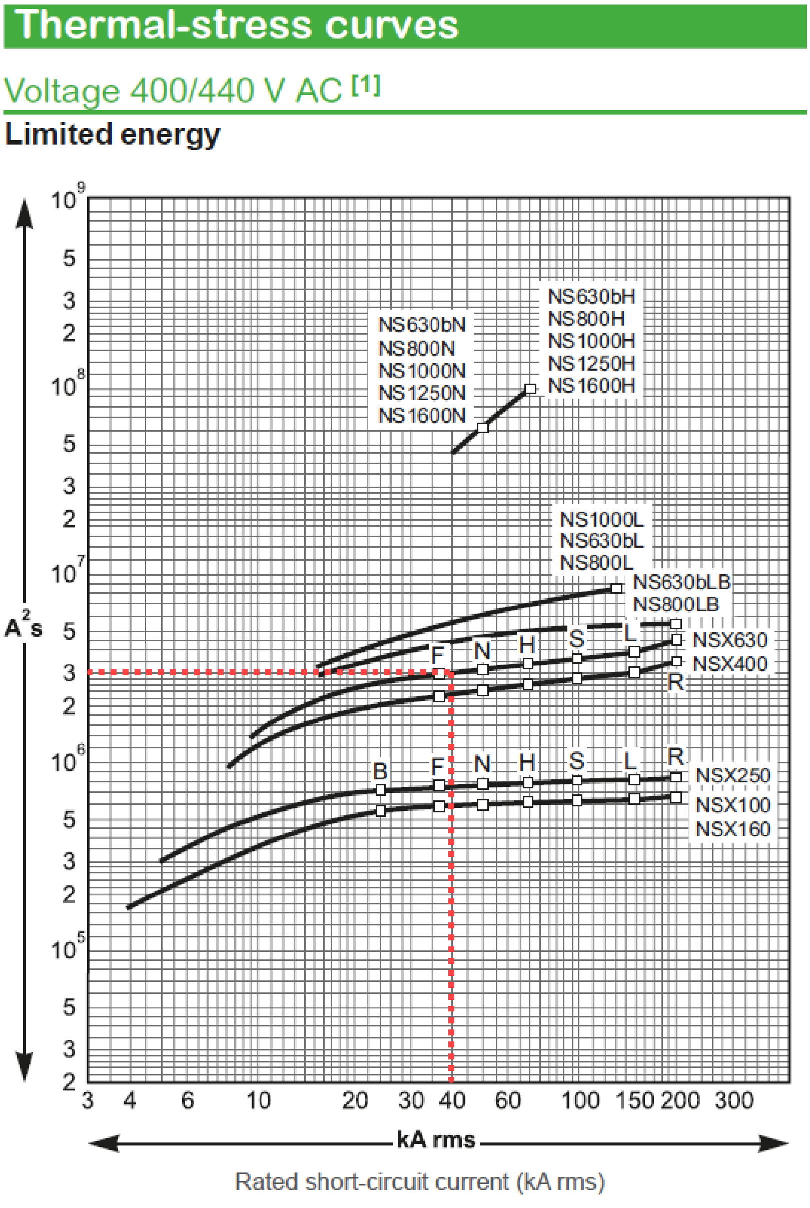
Now the fault current is > 799A which means the cable withstand ability will be violated if the trip time remains the same. So choose a bigger cable? Well, the results above show that ALL the cables are in trouble if the length is < 20m. In fact all the cables need to be around 30m to 34m or longer to ensure fault current is less than fault current rating.

So what to do if cable length is < 30m? A bit of a conundrum here!

Note – the magical 34m length (call it threshold length, TL) depends on the source, transformer and of course cable impedance as well as E for the given cable. Thus the TL will vary with each application. One solution could be to loop the cable so as to increase its length but this will have limited success especially where cable trays are already congested. It may also lead to additional derating having to be applied if in the vicinity of other cables.

The effect of current limiting (CL) breakers.

The let-through energy of CL breakers are available from manufacturer's data. The maximum let-through energy is given for a fault at the breaker location.



Thus, with a prospective fault current of 40kA, the maximum let-through energy of the NSX630 breaker is $3x10^6$ A^2.s.

It thus remains to ensure that the let-through energy of the breaker is less than the thermal capacity of the cable. Note that E is not dependant on the application but is a function of cable size and construction. Below is an extract of a table I constructed giving E for various cable sizes. A more conservative approach would be to ensure that the breaker (or fuse) let-through energy is < 0.8·E.

Cable Size	$1mm^2$	$1.5mm^2$	$2.5mm^2$	$4mm^2$	$6mm^2$	$10mm^2$	$16mm^2$
E =	20413	45929	127581	326608	734868	2041299	5225726
0.8·E =	16330	36743	102065	261286	587894	1633039	4180581
Cable Size	$70mm^2$	$95mm^2$	$120mm^2$	$150mm^2$	$185mm^2$	$240mm^2$	$300mm^2$
E =	100023669	184227268	293947110	459292359	698634710	1175788438	1837169435
0.8·E =	80018935	147381815	235157688	367433887	558907768	940630751	1469735548

Note that the above discussion is equally applicable for CL fuses.

Returning to the conundrum:

Advantage can now be taken of the fact that the cable only needs to be sized according to the let-through energy of the upstream CL breaker. The following table was constructed based on a prospective fault current of 47kA.

CL MCCB	Max let-through energy	$1mm^2$	$1.5mm^2$	$2.5mm^2$	$4mm^2$	$6mm^2$	$10mm^2$	$16mm^2$	$25mm^2$	$35mm^2$
S125GJ: 20A	500000	No	No	No	No	Yes	Yes	Yes	Yes	Yes
S125GJ: 32A	1000000	No	No	No	No	No	Yes	Yes	Yes	Yes
S125GF: 50A-125A	2600000	No	No	No	No	No	No	Yes	Yes	Yes
S250PE	3000000	No	No	No	No	No	No	Yes	Yes	Yes
S400GE	5500000	No	No	No	No	No	No	No	Yes	Yes

Thus what is the minimum cable size if the upstream breaker is a S125GL with a 20A trip unit? A $1.5mm^2$ cable has 0.8E = 16330 whilst the let-through energy of the breaker is 50000. A $1.5mm^2$ cable is thus undersized. The table says that the 1^{st} cable to meet the requirement is a $6mm^2$ one.

For a S250PE breaker, smallest allowable cable size is $25mm^2$. This does not imply that this is what the cable size must be. Other factors such as load and volts drop, etc. need to be considered as well.

Note:

1. Cable size based on let-through energy is not dependant on the length of the cable. Indeed as the fault location is further away from the breaker, the let-through energy decreases which improves the situation.
2. Cable sizing based on let-through energy implicitly account for DC offset in the fault current as well.

Finally, for our colleagues across the waters in the US, I found the following formula in a General Cables catalogue:

Curves Based on the Formula

$$\left[\frac{I}{A}\right]^2 t = 0.0297 \log_{10}\left[\frac{T_2 + 234}{T_1 + 234}\right]$$

I = Short Circuit Current–Amperes
A = Conductor Area–Circular Mils
t = Time of Short Circuit–Seconds
T_1 = Maximum Operating Temperature–90°C
T_2 = Maximum Short Circuit Temperature–250°C

Did a comparison check - used AWG 4 cable (41783.44cmil) plugged into the above formula. Then used the equivalent 21.15mm^2 cable and plugged it into Eq. 1. Results differed by about 1% which I would easily ascribe to all the rounding errors I made.

I am sure there would be a more general form of the above General Cables formula available to cater for conductors other than Cu and different initial and final temperatures. In essence, the above General Cables formula should be fine to determine E for a Cu cable, with initial and final temperatures as shown. It remains then to compare it to the max. let-through energy of the CL breaker to determine suitability for a given application.