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Specification of DC Time Constants for Switchgear

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Foreword

International standards define circuit-breaker terminal fault making & breaking capability in terms of a rated ac RMS current and a 100% dc component decaying with a single time constant. The standard value of dc time constant defined in circuit-breaker standard IEC 62271-100 is 45ms; a value which corresponds well to the dc time constant of overhead lines but which is significantly less than that of transformers (typically well in excess 100ms). Special case alternative values of 75ms and 120ms which can be selected by users are also included in the standard. In recent years ENA members have become concerned that the specification of a 45ms dc time constant may be inadequate for the UK network at 132kV and below and an ENA working group was set up to establish the requirements of the network (via fault level studies) and develop appropriate switchgear specifications. This report presents recommendations for revised switchgear specifications for incorporation into ENA Technical Specification documents in conjunction with the key elements of the work which justify these recommendations.

Scope

This Engineering Recommendation applies to switchgear at UK primary substations and above; it does not apply to UK distribution substations.

Report Recommendations

ENA should specify switchgear short-circuit ratings at two values of DC time constant; 45ms and 120ms.

ENA should accept that ratings proven at a DC time constant of 45ms can be extrapolated up to a DC time constant of 90ms but not beyond.

ENA should accept that ratings proven at a DC time constant of 120ms can be extrapolated up to a DC time constant of 270ms but not beyond.

ENA should accept that, providing adequate evidence of performance at 45ms and 120ms exists, interpolation can be used to derive ratings in the range 90-120ms.

Peak make/withstand ratings should be specified in accordance with IEC requirements based on the highest specified AC RMS short-circuit current and the associated dc time constant.

ENA should adopt the switchgear short-circuit ratings presented in Table 8 of this recommendation for use within ENA Technical Specifications namely:

Time constant	132kV 3 ph	132kV 1ph	66kV	33kV	20-25kV	11kV	6.6kV
45 ms	40kA	40kA	40kA	31.5kA	20 kA	25kA	25kA
120 ms	31.5kA	31.5kA	31.5kA	20kA	12.5kA	16kA	16 kA

Switchgear short circuit breaking current ratings for incorporation in ENATS

Introduction

The following report is presented in three main sections which describe:

- The key elements of fault current for switchgear ratings
- The fault level studies undertaken by ENA members
- The analysis of the survey results
- The derivation of recommended ratings for inclusion within ENATS

It is important to note that this report is presented on the basis of worst case, single phase fault conditions which result in the most onerous potential fault current interruption conditions for the circuit-breaker.

Key elements of fault current for switchgear ratings

Whilst real fault currents are complex in nature, particularly when considering the DC elements, they can be adequately described as the summation of three distinct components as follows:

AC synchronous fault level. This is the “steady state” fault contribution of connected sources which does not vary within the timescale of interest within this report.

AC transient fault in-feeds. This is the contribution from local rotating equipment, such as induction motors, which decays within the timescale of interest within this report. Further details of this contribution and the modelling of it can be found in ER G74.

DC component. This is a component which is generated by inductive elements of the system in response to the virtually instantaneous change in AC current at fault initiation. This component decays with a time constant dictated by local system components and is typically in the range 40ms to 200ms depending upon the balance between resistive and inductive elements.

The AC contributions to the fault current waveform are illustrated in Figure 1. This figure shows the fault occurring at the time of peak current (voltage zero) and these contributions add together as shown in Figure 2.

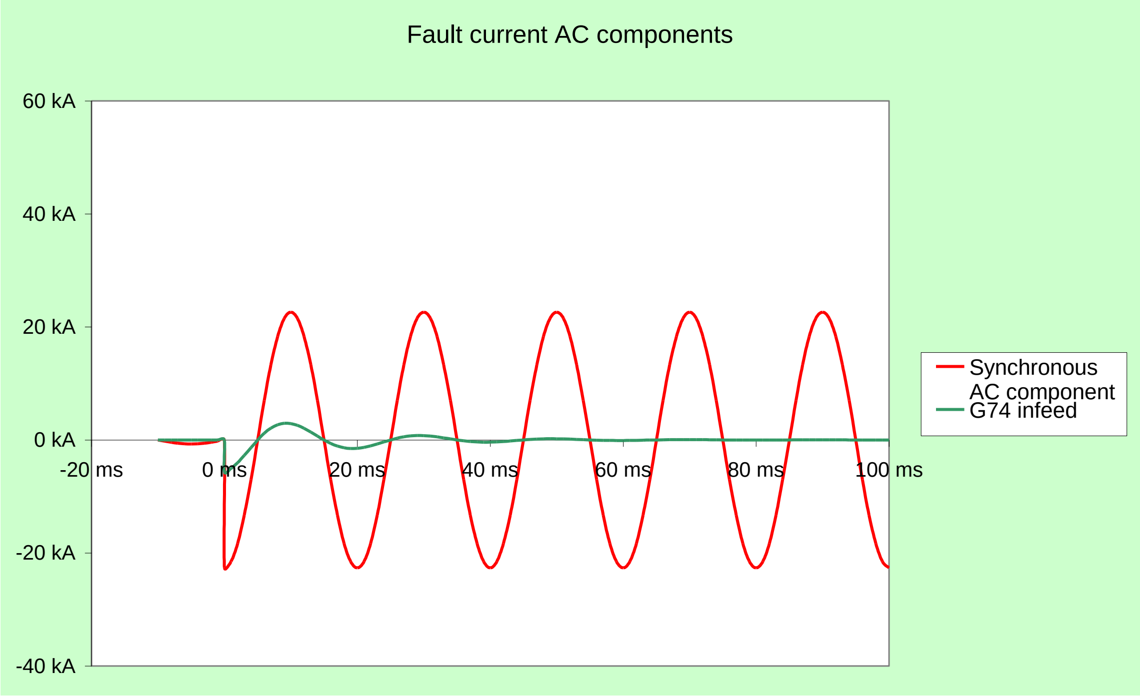


Figure 1: Typical AC fault current contributions

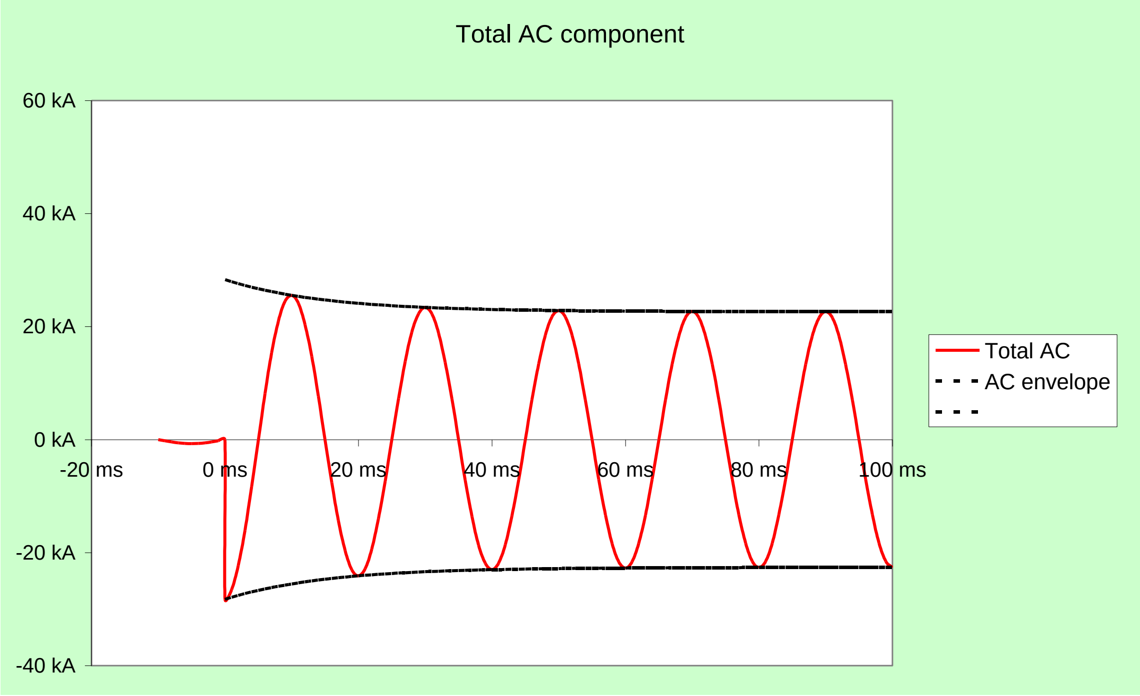


Figure 2: Total AC fault current contribution

It can be clearly seen that the envelope of the AC current decays from its initial magnitude to the steady state value over a short time following fault initiation.

The above figures show the current instantaneously rising to a high value. However, due to the system inductance, the current cannot instantaneously change as shown and a DC component is generated to counteract this sudden change. The DC component decays in a relatively complex manner however, for the purposes of simplification when specifying switchgear, it is considered to decay with a single time constant governed by the X/R ratios of the circuits feeding the fault.

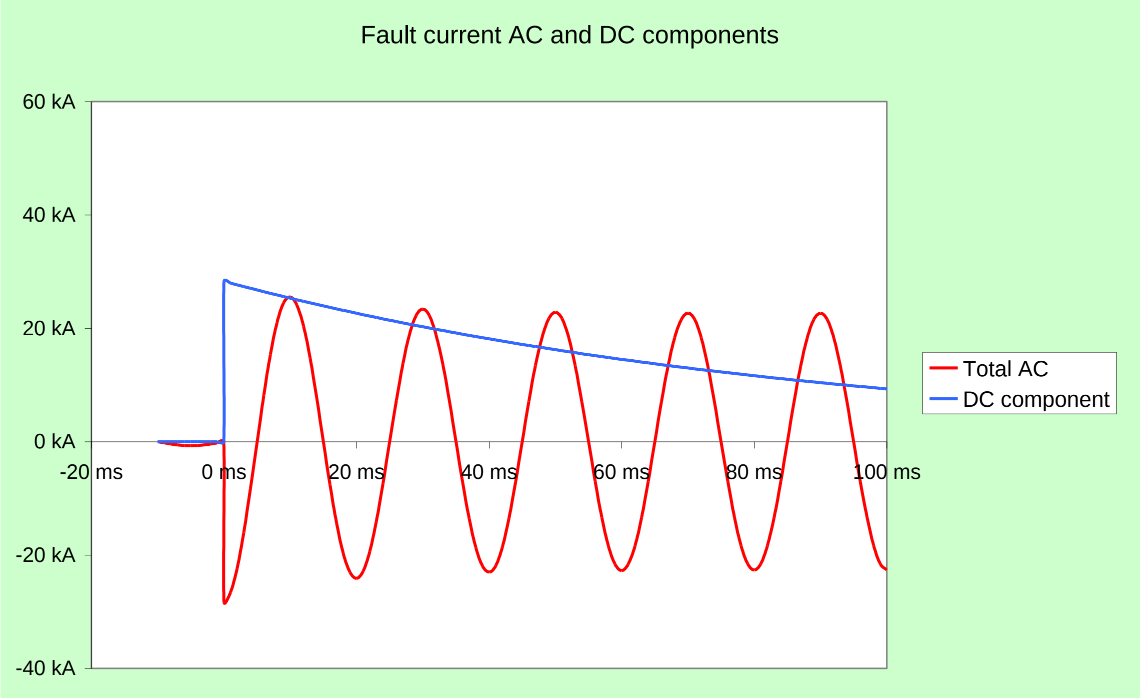


Figure 3: AC & DC fault current contributions

Figure 3 shows both the AC and DC components and Figure 4 shows the resultant total fault current and highlights the key features which are relevant for switchgear performance and hence specification. These can be described as follows:

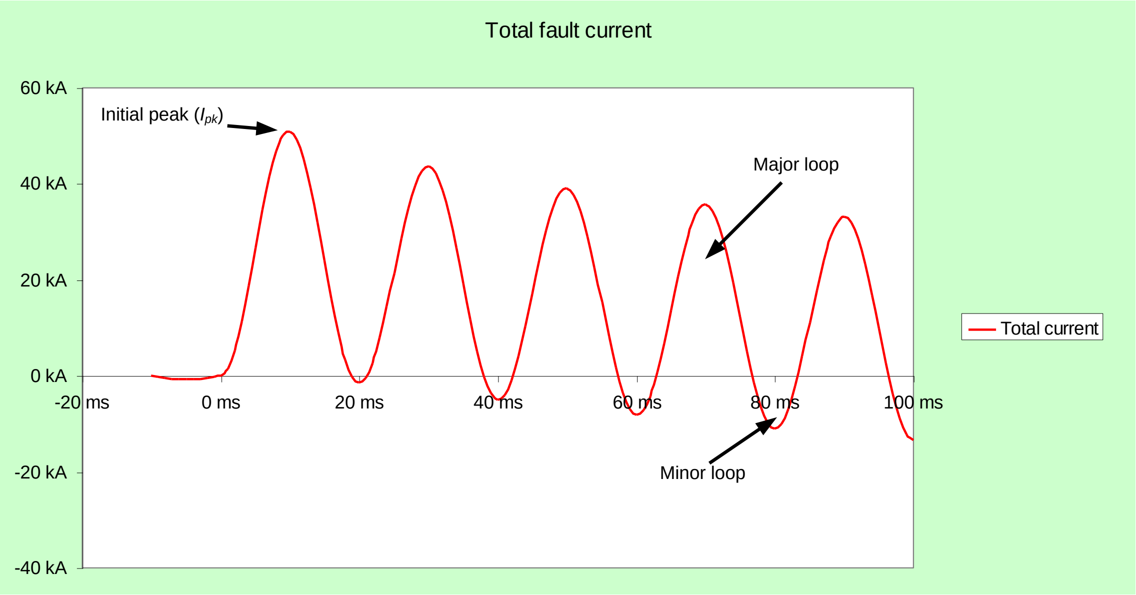


Figure 4: Total fault current

Initial peak current. This is the peak current, occurring at approximately 10ms from fault initiation (50Hz system), which all series connected equipments must be able to withstand and which circuit-breakers must be able to safely close onto (termed making). It is largely determined by the values of the synchronous fault current and the G74 in-feed current. The value of the time constant has a limited effect, with longer time constants increasing the value slightly.

Total breaking current during arcing period. During opening the circuit-breaker will be subject to the asymmetric current as shown in Figure 4 and, in particular, to a sequence of major & minor current loops. The current behaviour during the very early part of the fault, when the circuit-breaker contacts remain closed, is of limited interest. However, following contact separation the circuit-breaker is required to control the resultant arcing until a suitable current zero for interruption occurs and also to withstand that resultant transient recovery voltage. Due to the relatively high energy associated with the major loops of fault current and the irregular occurrence of current zeroes this is a potentially onerous requirement for circuit-breakers.

It is widely accepted [1] that, in order to assess the ability of circuit-breakers to operate where the effective system DC time constant exceeds the tested value, a comparison of the first full major loop of fault current following contact separation is appropriate. In doing this, the following aspects of the major loop must be considered.

Peak breaking current. This is determined by the value of the synchronous fault current and the DC time constant. A longer time constant results in a higher degree of asymmetry and has a significant effect on the value of the peak current.
Arc energy. This is a function of the current and voltage in the major loop. It is widely accepted that the arc voltage can be considered constant and hence that a comparison of the major loop area is sufficient to compare arc energies.
Duration of major loop. The length of the major (and minor) loops and hence the arcing time characteristics of the circuit-breaker during interruption are affected by the effective DC time constant. Higher DC components significantly increase the length of major loops.

On the basis of the above approach, fault level studies on the UK networks in the range between 132kV and 11kV have been used to derive recommendations for future ENA switchgear short-circuit current specification. Further details of the method used are presented in later sections of this document.

Fault level studies undertaken by ENA members

In order to obtain relevant data for assessment each DNO, plus National Grid where relevant, was asked to provide the fault level and X/R ratio for every circuit-breaker on their network within the scope of the project.

Table 1 outlines the total number of circuit breakers and the major circuit configurations used in the survey.

Voltage (kV)	Number of Sites	Number of Breakers	Breakers on Transformer LV	Not on Transformer LV
132	348	1648	915	733
66	140	787	311	476
33	1078	7457	5912	1545
20 - 25	95	596	548	48
11	2829	27603	27540	63
6 - 6.6	164	1645	1613	32
Totals	4654	39736	36839	2897

Table 1: Number of circuit-breakers used in the survey of fault data

It was identified early in the process that, if a national survey of fault levels was undertaken, the results provided by each member company might not be directly comparable with each other due variations in tools and methodologies. In an attempt to mitigate this, a benchmarking exercise was undertaken to ascertain the variation in results for a pre-determined set of data.

A simple test network was devised and all member companies used their existing modelling tools and methodologies to calculate the prospective make and break duties. A benchmark set of results was also calculated using an electromagnetic transient programme to accurately calculate the fault current characteristics of the network. The network used for the benchmarking exercise is shown in Appendix 1. The results, including the reference results from EMTP, are given in Appendix 2. The results of this indicate that:

1. Values of initial peak and ac currents in the majority of cases are close to the true values;
2. Values of %dc and peak break currents (which are directly related) show greater variation, with some giving more onerous, and others less onerous, duties. However the majority are close to the true results.

Note: the results of the benchmarking exercise led some member companies to review their methodologies for calculating fault levels.

The results of the survey showed significant variations in the results obtained by member companies. While the results of the benchmarking exercise demonstrated differences in calculated fault levels and DC time constants, comparison of the benchmarking results indicates that the effect of this will be to broaden the range of time constants reported, but not to affect the ac fault current values significantly. The working group agreed that it was up to individual member companies to satisfy themselves that they were happy with their calculation methods and associated results.

It should also be noted that, being based upon an intact network condition, not all system conditions are fully addressed. In particular, recent experience suggests that the survey fault levels do not adequately cover for 132kV National Grid/DNO interface sites in non-standard configurations (e.g. four transformer sites which go from 2+2 to 3+1 running during outage works). A 31.5kA, 120ms rating at 132kV has been incorporated into the recommendations of this report to cater for this. This is not expected to alter the equipment offered to DNO's or ENASAP for assessment.

Analysis of the survey results

The key data from the survey is presented in Appendices 3, 4 & 5. Appendix 3 summarises the results of the survey. Appendix 4 shows the fault level at each circuit-breaker plotted against the effective DC time constant for the various cases (the DC time constant is 3.18 times the X/R ratio). Appendix 5 presents the distribution of DC time constants analyses by frequency of occurrence.

Tables 2 and 3 summarise the fault levels and DC time constants respectively falling within 90%, 95% and 99% percentiles i.e. those values below which 90%, 95% and 99% of the survey results lie.

Percentile values	**132kV 3 ph**	**132kV 1 ph**	**66kV**	**33kV**	**20-25kV**	**11kV**	**6.6kV**
90%	17.6 kA	21.3 kA	16.8 kA	16.0 kA	10.6 kA	11.5 kA	17.5 kA
95%	18.7 kA	22.8 kA	17.2 kA	17.7 kA	11.0 kA	12.5 kA	19.2 kA
99%	19.4 kA	24.5 kA	17.2 kA	21.5 kA	13.0 kA	14.8 kA	23.5 kA

Table 2: Analysis of Fault levels from survey

Percentile values	**132kV 3 ph**	**132kV 1 ph**	**66kV**	**33kV**	**20-25kV**	**11kV**	**6.6kV**
90%	148 ms	120 ms	139 ms	110 ms	97 ms	93 ms	89 ms
95%	158 ms	135 ms	148 ms	131 ms	133 ms	124 ms	112 ms
99%	248 ms	157 ms	231 ms	172 ms	160 ms	235 ms	293 ms

Table 3: DC time constants

Derivation of recommended ratings

A CIGRÉ paper [2] has proposed that the capability of circuit-breakers to interrupt a fault current with a higher DC time constant than tested may be based on the following criteria:

- The major loop peak current during arcing is no higher than that tested.
- The arcing energy (equivalent to the integral of current) is no higher than that tested.
- The value of dI/dt (which determines the transient recovery voltage) is no higher than that tested.

In practice, the last condition does not represent a limitation since a higher degree of asymmetry results in current zero crossings which are closer to the current peaks and hence the rate of change of current will be lower than would be the case for lower degrees of asymmetry.

Against these criteria, the following procedure has been used to evaluate the capability of circuit-breakers at DC time constants higher than 45 ms (the standard value for IEC 62271-100).

1. IEC 62271-100 specifies that circuit-breakers should be tested for asymmetrical duties at an opening time equivalent to the minimum opening time of the circuit-breaker plus 10 ms. On this basis it is considered that the first realistic major loop to be considered will be the loop centred on 50ms. To cover a variety of credible cases calculations have been performed for the major loops centred on 50ms, 70ms and 90ms.
2. For time constants from between 45ms and 300 ms the times for zero crossings at the start and finish of the major loops were calculated.
3. The integral of the arcing current for this period was calculated for a 1kA fault current.
4. For each major loop (50ms, 70ms, 90ms) the peak currents were calculated for the range of time constants.

From this procedure it was concluded that the limiting factor in all cases is the arc energy. For each value of time constant an AC de-rating factor was calculated to ensure that the integral of arcing current (arc energy) was no greater than that for the reference current with 45ms DC time constant. By plotting these values graphically it was shown that a lower rating (higher de-rating factor) was derived based on the 90 ms major loop than the 50ms and 70ms loops. The 90ms loop was therefore chosen as the basis for further work.

Using Microsoft Excel it was found that a polynomial equation of the following form gave a good fit for the relationship between the de-rating factor and the DC time constant over the range of time constants considered:

$$I_{\%} = a + b\tau + c\tau^2 + d\tau^3 + e\tau^4 + f\tau^5$$ (Formula for extrapolation from 45 ms ratings)

Where the coefficients are:

a	1.5803
b	-0.018476
c	1.5101 x 10-4
d	-6.7533 x 10-7
e	1.5574 x 10-9
f	-1.4456 x 10-12

Using this approach and the data from the fault level survey, AC RMS ratings (based on a tested DC time constant of 45ms) were calculated that would be sufficient to meet the 90th, 95th & 98th percentile of studied system requirements. It is important to note that “negative” de-rating factors i.e. increases in AC RMS capability on the basis of DC time constants of less than the reference value (45ms) are not permitted in the assessment.

The resultant values are shown in Table 4 and the derating curves for these ratings are plotted on the graphs in Appendix 4

Percentile values	**132kV 3 ph**	**132kV 1 ph**	**66kV**	**33kV**	**20-25kV**	**11kV**	**6.6kV**
90%	23.1 kA	25.7 kA	24.4 kA	22.2 kA	14.4 kA	13.4 kA	19.2 kA
95%	25.7 kA	26.2 kA	26.3 kA	25.1 kA	15.1 kA	16.2 kA	21.3 kA
99%	26.6 kA	29.1 kA	26.4 kA	28.7 kA	18.0 kA	21.2 kA	25.6 kA

Table 4: Ratings (tested DC time = 45ms) to address 90/95/99% of study requirements

A further constraint placed upon extrapolation of type test evidence to address increased DC time constants pertains to the percentage increase in length of the major loop. Whilst this aspect has not been widely recognised internationally, an unlimited increase in major loop length implies that circuit-breakers are not affected in any way by the time at which current zeroes appear. Whilst this may be true for some technologies it is not a generally applicable assumption and hence some provision should be made for it within the extrapolation & rating assessment process. To date a value of 15% has been used by some ENA member companies as the maximum allowable increase in major loop duration from type test to service conditions. This allows, for example, an extrapolation from a tested time constant of 45ms to a service condition of 90ms but not beyond.

The adoption of this limit of 15% is recommended here and thus, assuming standard type testing based on 45ms, system requirements in excess of 90ms create the need for type testing at a higher DC time constant.

IEC 62271-100 allows alternative time constants of 60ms, 75ms and 120ms to be specified. Whilst a time constant of 120 ms does not directly cover all of the requirements of the networks, applying the 15% increase in loop length would allow ratings base on 120ms to be extrapolated up to DC time constants of 270ms; well in excess of the vast majority of system requirements.

In line with the earlier discussed procedure, a formula has also been derived for extrapolating ratings from 120 ms ratings, as follows

$$I_{\%} = a + b\tau + c\tau^2 + d\tau^3 \text{ (formula for extrapolation from 120 ms ratings)}$$

Where the coefficients are:

a 1.609
b -0.007669
c 2.5056 x 10-5
d -2.9932 x 10-8

Table 5 below shows the equivalent ratings for the circuit-breaker sites in the DNO survey, using a DC time constant of 120ms.

Percentile values	132kV 3 ph	132kV 1 ph	66kV	33kV	20-25kV	11kV	6.6kV
90%	15.2 kA	16.9 kA	16.7 kA	14.6 kA	9.5 kA	8.8 kA	12.6 kA
95%	16.9 kA	17.2 kA	17.3 kA	16.5 kA	9.9 kA	10.7 kA	14.0 kA
99%	17.5 kA	19.2 kA	17.3 kA	18.9 kA	11.9 kA	14.0 kA	16.9 kA

Table 5: Ratings (tested DC time = 120ms) to address 90/95/98% of study requirements

Within IEC, standard ratings are selected from the R10 series. Tables 6 & 7 re-present the data of Tables 4 & 5 with current values enhanced to an appropriate standardised value.

Percentile values	132kV 3 ph	132kV 1 ph	66kV	33kV	20-25kV	11kV	6.6kV
90%	25 kA	31.5 kA	31.5 kA	25 kA	16 kA	16 kA	20 kA
95%	31.5 kA	31.5 kA	31.5 kA	31.5 kA	16 kA	20 kA	25 kA
99%	31.5 kA	31.5 kA	31.5 kA	31.5 kA	20 kA	25 kA	31.5 kA

Table 6 Circuit-breaker equivalent R10 ratings for 45 ms DC time constant

Percentile values	132kV 3 ph	132kV 1 ph	66kV	33kV	20-25kV	11kV	6.6kV
90%	16 kA	20 kA	20 kA	16 kA	10 kA	10 kA	16 kA
95%	20 kA	20 kA	20 kA	20 kA	10 kA	12.5 kA	16 kA
99%	20 kA	20 kA	20 kA	20 kA	12.5 kA	16 kA	20 kA

Table 7 Circuit-breaker equivalent R10 ratings for 120 ms DC time constant

On the basis of a required level of coverage (90/95/99%) these tables provide the minimum recommended short-circuit capability that should be incorporated into ENATS specifications.

However for 132kV and 66kV circuit-breakers higher ratings are recommended in order to allow for abnormal running arrangements due to SGT outages.

Conclusions

ENATS should specify short-circuit ratings at two values of DC time constant; 45ms and 120ms.

ENA should accept that ratings proven at a DC time constant of 45ms can be extrapolated up to a DC time constant of 90ms but not beyond.

ENA should accept that ratings proven at a DC time constant of 120ms can be extrapolated up to a DC time constant of 270ms but not beyond.

ENA should accept that, providing adequate evidence of performance at 45ms and 120ms exists, interpolation can be used to derive ratings in the range 90-120ms.

Peak make/withstand ratings should be specified in accordance with IEC requirements based on the highest specified AC RMS short-circuit current and the associated dc time constant. As an example, at 132kV, the peak requirements would be based on 40kA & 45ms giving a peak factor of 2.5 (100kA.pk).

ENA should adopt the switchgear short-circuit ratings presented in Table 8 for use within ENATS.

Time constant	132kV 3 ph	132kV 1ph	66kV	33kV	20-25kV	11kV	6.6kV
45ms	40kA	40kA	40kA	31.5kA	20 kA	25kA	25kA
120ms	31.5kA	31.5kA	31.5kA	20kA	12.5kA	16kA	16 kA

Table 8: Switchgear short circuit breaking current ratings for incorporation in ENATS

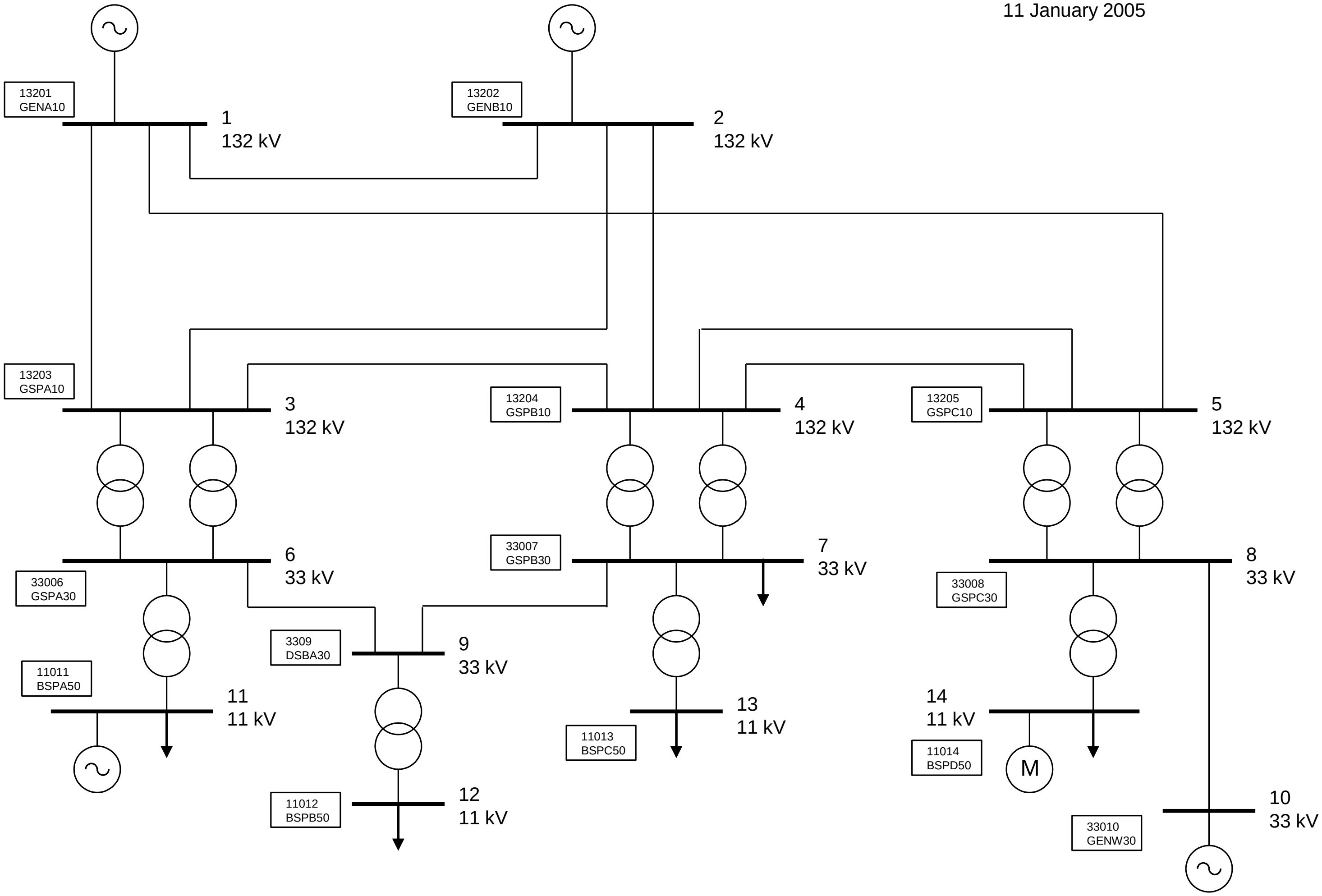
For 132kV and 66kV circuit-breakers higher ratings are recommended in order to allow for abnormal running arrangements due to SGT outages.

References

[1] CIGRE Technical Brochure No. 304
[2] Consideration of X/R ratio in the application of high-voltage circuit-breakers. CIGRÉ internal WG paper A3-03(WG11)17

Appendix 1 - Test Network for Benchmark Study

Benchmark Network R6
11 January 2005



BENCHMARK NETWORK DATA FOR ASG/OSG X/R SUB-GROUP

All values are p.u. on 100MVA unless indicated otherwise

NODE DATA

Node	PSS/E Node	Name	Voltage (kV)	Busbar Type	Voltage Setpoint		Loadflow Solution	
							V (p.u.)	**Ang (deg)**
1	13201	GENA10	132	Slack	1.0000		1.0000	0.00
2	13202	GENB10	132	PV	1.0000		1.0000	0.13
3	13203	GSPA10	132	PQ			0.9976	-0.35
4	13204	GSPB10	132	PQ			0.9963	-0.53
5	13205	GSPC10	132	PQ			0.9984	-0.40
6	33006	GSPA30	33	PQ			1.0029	-1.01
7	33007	GSPB30	33	PQ			0.9994	-2.55
8	33008	GSPC30	33	PQ			1.0023	-0.74
9	33009	DSBA30	33	PQ			0.9818	-2.28
10	33010	GENW30	33	PV	1.0100		1.0100	-0.58
11	11011	BSPA50	11	PQ		Generator at busbar, but not a PV busbar. Generator Q fixed at 0.1 MVAr	1.0080	-6.04
12	11012	BSPB50	11	PQ			1.0171	-4.90
13	11013	BSPC50	11	PQ			1.0117	-7.27
14	11014	BSPD50	11	PQ			1.0117	-5.79