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1. INTRODUCTION

There has been an inconsistent approach to rating switch-gear and the calculation of fault currents to determine this rating. This has led to switch-gear being over-rated in many instances within ESKOM. The need therefore arose to standardise the approach within the Electrical Engineering Department of ESKOM.

There have been various arguments presented on the applicability of the different parameters, defined in IEC 60909, associated with fault currents and as applied to equipment rating. This has particular reference to the rating of both MV & LV switch-gear. The document discusses the approach to fault current calculations, the effect of induction machines and the rating MV & LV switch-gear. The interpretation of the results produced by the currently used software package, DigSilent, will also be discussed. The document further considers alternative methods of addressing the impact of induction machine contributions on the fault current. The discussion is limited to three phase faults

A sample simulation using a time domain simulation software package, PSCAD, is presented and used to explain the various components of the fault current. The results produced using the four different methods will be presented in the document for a sample network.

2. SUPPORTING CLAUSES

2.1 SCOPE

The scope of this document is limited to fault current calculations, the effect of induction machines on fault currents and the ratings associated with breakers. The fault consideration is limited to a three phase fault that occurs far from a generator.

2.1.1 Purpose

See introduction

2.1.2 Applicability

This document shall apply throughout Eskom Holdings Limited Divisions.

2.2 NORMATIVE/INFORMATIVE REFERENCES

2.2.1 Normative

[1] Short circuit currents in three phase AC systems, IEC, 60909-0, 2001.

[2] Short circuit currents in three phase AC systems; Examples for the calculation of short circuit currents, IEC, 60909-4, 2001.

[3] PSCAD/EMTDC evaluation edition, Manitoba HVDC Research, V4.2.1,2006

[4] Elements of Power System Analysis, Stevenson W.D, 2nd edition, 1962

[5] DigSilent Power Factory, V13.2.336

[6] Short-circuit current calculations, Application Information, General Electric

[7] Calculating short-circuit currents with Contributions from Induction Motors, Huening W.C. Jr, IEEE Transactions on Industry Applications, Vol 1A-18, No. 2, March/April 1982

[8] Power System Analysis & Design, Glover Sarma, 2nd Edition, 1993

2.2.2 Informative

None

2.3 DEFINITIONS

Definition	Description
$I_k^"$	RMS value of the AC symmetrical component of a prospective short-circuit current applicable at the instant of short circuit if the impedance remains at zero-time value
i_p	Maximum permissible instantaneous value of the available short-circuit current
I_b	RMS value of an integral cycle of the symmetrical AC component of the available short-circuit current at the instant of contact separation of the first pole to open of a switching device
I_k	RMS value of the short circuit current which remains after the decay of the transient phenomena
Near-to-generator short circuit	Short circuit to which at least one synchronous machine contributes a prospective initial symmetrical short circuit current which is more than twice the machines rated current, or a short circuit to which asynchronous motors contribute more than 5% of the initial symmetrical short circuit current without motors

2.3.1 Disclosure Classification

Controlled Disclosure: controlled disclosure to external parties (either enforced by law, or discretionary).

2.4 ABBREVIATIONS

Abbreviation	Description
3Φ	Three phase
a.c	Alternating current
d.c	Direct current
EFP	Electric feed pump
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronic Engineers
IEEE Violet Book	Recommended Methods for Calculating AC Short-circuit currents in Industrial & Commercial Power Systems
LV	Low voltage
MV	Medium voltage
U_n	System nominal voltage

2.5 ROLES AND RESPONSIBILITIES

None

2.6 PROCESS FOR MONITORING

None

2.7 RELATED/SUPPORTING DOCUMENTS

None

3. FAULT CURRENT CALCULATIONS AND RATING SWITCH GEAR

3.1 BACKGROUND

3.1.1 Asynchronous Machines and Fault Current Contribution

Induction machines are frequently utilised in industry and appear in a host of applications. In recent years the size of these machines has increased dramatically. This has had an impact on the currents generated back into the supply network under faults conditions close to the machine. A key consideration, for the course of this discussion, is the constant stator flux present in the machine required for proper operation. The value of this flux constant is calculated as

$$K = \frac{V}{f} \qquad (1)$$

and is a constant ratio of the applied terminal voltage and frequency. This flux appears in the rotor but at the slip frequency. The rotor flux remains normal as long as voltage is applied to the stator from an external source [[6]]. If a short circuit occurs close to the machine terminals and the stator voltage falls to zero the stator flux follows suit and therefore the rotor flux. The mechanism of the fault current contribution is a result of the stator driving voltage generated by the trapped rotor flux [[7]]. This current comprises of both an a.c and d.c component. Figure 1 below illustrates the fault current waveform obtained from laboratory tests of a 112kW motor subjected to a terminal short circuit. The figure shows time on the x-axis and multiple of full load current of the motor in *kA* on the y-axis.

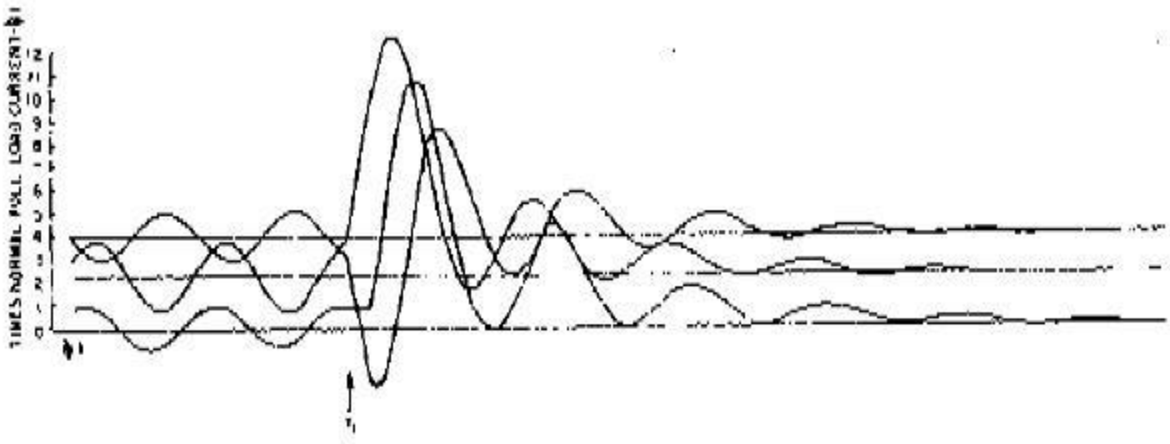

Figure 1: Three Phase Short-Circuit Current from an Induction Motor Running at Full Load

The AC component decays because the rotor flux is not maintained by normal applied voltage [[7]]. The DC component is not supported by a driving voltage and also decays. The frequency differs initially from the system frequency by motor slip and thereafter reduces at a rate dependent on motor mechanical load and combined motor and load inertia. For the first few cycles this frequency change can be neglected. The initial magnitude of the a.c component is calculated using the subtransient motor impedance $Z^{"}$. It is accepted practice to substitute the known or estimated locked rotor impedance Z_{LR} for $Z^{"}$, [[7]]. In general the load current drawn by the motor at the instant the fault is applied is neglected in the calculation for the fault current contribution. The justification is that the magnitude is small relative to the fault current generated, [[8]]. This may not be entirely accurate as is the case with the EFP motor's considered later in the document. To account for this the load current must be subtracted from the generated fault current during the calculations.

The equation to be used to calculate the fault current generated by the machine is therefore given by:

$$\hat{I}_{km}'' = I_{km}'' - I_L \qquad (2)$$

where

$\hat{I}_{km}''$ is the actual RMS symmetrical fault current generated by the machine

I_{km}'' is the initial RMS symmetrical current

I_L is the load current drawn by the machine at the instant of the fault occurrence.

These factors infer that a significant fault current contribution from induction machines last 1.5 to 4 cycles, based on 60Hz corresponding to 16.67msec per cycle, after fault inception. The cycle times are important and their implication will be discussed further in the following sections.

The a.c and d.c fault current components, as a function of time, can be calculated using the following equations, [[7]]:

$$I_{ac} = \left(\frac{E}{Z''}\right) e^{-(2\Pi t / T_d'')}; \; I_{dc} = \sqrt{2} * \left(\frac{E}{Z''}\right) e^{-(2\Pi t / T_a)} \qquad (3, 4)$$

where the symbols have the following meaning

$$T_d'' = \frac{X''}{R_R} \text{ , } R_R \text{ is the rotor resistance} \qquad (5)$$

$$T_a = \frac{X''}{R_S} \text{, } R_S \text{ is the stator resistance} \qquad (6)$$

If any series impedance exists between the terminals of the motor and the fault the time constants should be modified to include this resistance as follows,

$$T_d'' = \frac{X'' + X_e}{R_R} \qquad ; T_a = \frac{X'' + X_e}{R_S + R_e} \qquad (7, 8)$$

X_e and R_e represent the equivalent impedance between the fault location and the terminals of the machine. To calculate the short-circuit contribution at a specific time, t_s, one approach is to introduce an impedance multiplying factor. This factor is suggested in [[7]] as being $e^{+t_S / T_d''}$.

Typical RMS simulation studies and short-hand calculations fail to adequately address this exponential ac decay phenomenon present in the induction machine fault current contribution. An example will be presented in §3.2 of this document to illustrate this. Parts of the discussion presented in [[7]] forms sections of the IEEE Violet Book.

3.1.2 Breaker Capabilities and Associated Ratings

All MV breakers are characterized by two important rating parameters. These are the peak-making current and the steady-state current carrying capability. A third important inherent parameter is the symmetric breaking current capability. This is considered by manufacturers as being equal to the steady-state current rating of the breaking. This is the current the breaker is expected to interrupt under a fault condition. The breaking current is a system dependent parameter and is determined by the time constant of the network. It is the current present at the instant of operation of the first pole of the breaker. This is typically the value of the fault current 100msec after fault inception. This is a realistic assumption since most breakers can only operate between 80-100msec with exceptions being 60msec. The peak making fault current is defined as the maximum possible current the breaker will experience in the event of inadvertent closure onto a fault. This is approximately 2.5 times the RMS steady-state fault current and is also dependent on the system *X/R* ratio. The steady-state current is defined as the current the breaker can carry uninterrupted for three seconds. As an example a breaker with a steady-state fault current capability of 31.5kA has a peak fault making current capability of 80kA. Modern circuit breaker standards are based on symmetrical interrupting current, [[8]]. It is usually necessary to calculate only symmetrical fault current at a system location, and then select a breaker with a symmetrical interrupting capability equal to or above the calculated current. The breaker has the additional capability to interrupt the asymmetrical (or total) fault current if the DC offset is not too large, [[8]].

3.1.3 IEC– Short Circuit Currents in 3φ AC Systems

A complete calculation of the fault current should give the currents as a function of time at the short circuit location, from initiation of the short circuit up to its end, corresponding to the instantaneous value of the voltage at the beginning of the short-circuit. The fault current takes on the waveform illustrated in Figure 2.

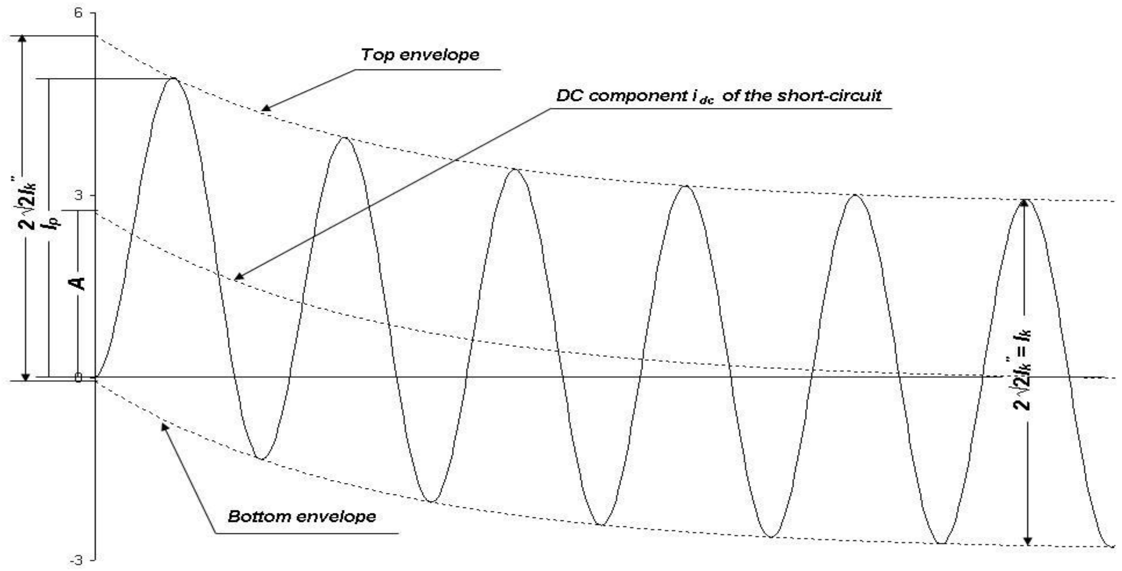

Figure 2: Short-Circuit Current of a Far-From Generator Short-Circuit With Constant A.C Component

The symbols in the figure have the following meaning

I_k'' = Initial symmetrical short-circuit current

i_p = peak short-circuit current

I_k = steady-state short-circuit current

i_{dc} = d.c component of short-circuit current

A = initial value of the d.c component i_{dc}

Depending on the application of the results, it is of interest to know the RMS value of the symmetrical a.c component and the peak value of the short-circuit current. This peak value is dependent on the time constant of the decaying aperiodic component and the frequency. The time constant is determined by the system *X/R* ratio. The peak illustrated is only achieved if the short-circuit starts at zero voltage and also depends on the decay of the symmetrical a.c component of the short-circuit current.

(1) The specification considers that the current in a 3Φ short circuit is assumed to be made simultaneously in all poles of the interrupting device.

3.1.3.1 Methods of Calculation

3.1.3.1.1 Equivalent Voltage Source at the Short-Circuit Location

This approach is based on the introduction of an equivalent voltage source at the short-circuit location and is the only active voltage of the system. Asynchronous machines, synchronous machines and network feeders are replaced by their internal impedances. This data is sufficient to determine the fault current at the chosen location and all other details such as load flows become superfluous. **If no guideline exists on the allowable operating range of the system voltage a voltage factor can be chosen according to Table 1**.

Table 1: Voltage Factor *c*

Nominal Voltage U_n	Voltage factor *c* for the calculation of	
	Max short-circuit currents C_{max} (1)	Min short-circuit currents C_{min}
Low voltage 100V to 1000V	$1.05^{(3)}$ $1.10^{(4)}$	0.95
Medium voltage >1kV to 35kV • High voltage • >35kV	1.10	1.00
(1) $c_{max}U_n$ should not exceed the highest voltage U_m for equipment of power systems (2) If no nominal voltage is defined $c_{max}U_n = U_m$ or $c_{min}U_n = 0.9*U_m$ should be applied (3) For low voltage systems with a tolerance of +6%, for example systems renamed from 380V to 400V (4) For low voltage systems with a tolerance of +10%		

In the current application of this standard there is only interest in determining the maximum short-circuit current available. To achieve this, an appropriate voltage factor according to the table above should be applied. The contributions of induction motors to the fault current shall be included if appropriate and is dealt with in the next section of this document.

3.1.3.1.2 Impact of Induction Machines on Fault Current According to IEC 60909-0

a. General

The IEC specification states that medium and low voltage induction motors contribute to the initial symmetrical short-circuit current, I_k'', to the peak short-circuit current, i_p, to the symmetrical short-circuit breaking current, I_b and for unbalanced short-circuits to the steady-state short-circuit, I_k. The specification also states that medium voltage motors have to be considered in the calculation of maximum short-circuit currents.

The contribution of asynchronous motors in low voltage power supply systems to the short-circuit current, $I_k^{"}$ may be neglected if their contribution is not higher than 5% of the initial short-circuit, $I_{kM}^{"}$ calculated without motors.

The following equation given in the specification is a method to check for the applicability of including LV motors in the calculation for fault current.

$$\sum I_{rM} \leq 0.01 * I_{kM}^{"}$$

where

$\sum I_{rM}$ is the sum of the rated currents of motors connected directly (without transformers) to the network where the short-circuit occurs

$I_{kM}^{"}$ is the initial symmetrical short-circuit current without influence of motors.

In the calculation of short-circuit currents, MV and LV motors may be neglected provided that according to the circuit diagram or to the process, they are not switched in at the same time, [[1]].

b. Contribution to Short-Circuit Currents by Asynchronous Machines

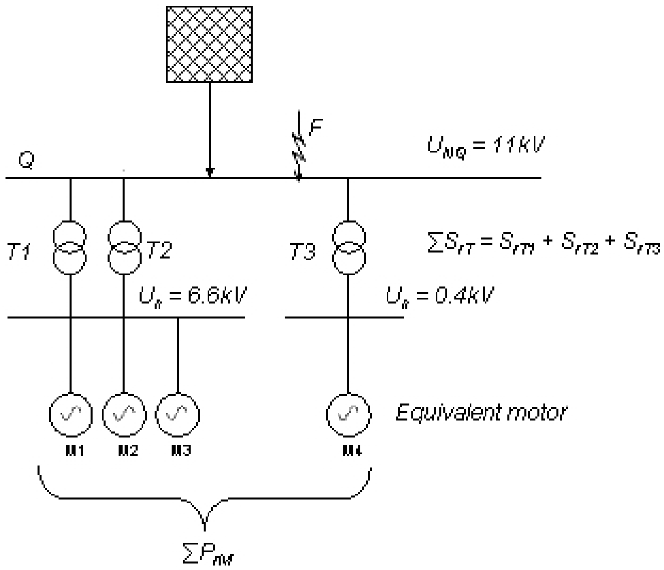

Figure 3: Simplified Network Structure

Medium and low voltage induction machines which are connected by two winding transformers to the network in which the short-circuit occurs, may be neglected in the calculation of short-circuit currents for a short at the feeder connection point Q in Figure 3, if:

$$\frac{\sum P_{rM}}{\sum S_{rT}} \leq \frac{0.8}{\left| \frac{c * 100 * \sum S_{rT}}{\sqrt{3} * U_{nQ} * I''_{kQ}} - 0.3 \right|} \quad (10)$$

where:

$\sum P_{rM}$ is the sum of the rated active powers of the MV & LV motors which shall be considered

$\sum S_{rT}$ is the sum of the rated apparent powers of all transformers, through which the motors are directly fed

I''_{kQ} is the initial symmetrical short-circuit current at the feeder connection point *Q* without supplement of the motors

U_{nQ} is the nominal voltage of the system at the feeder connection point *Q*

3.1.3.2 Calculation of Short-Circuit Currents

In the case of a near-to-generator short-circuit, the short-circuit current can be considered as the sum of the following two components:

- the AC component with decaying amplitude during the short-circuit
- the aperiodic DC component beginning at some value, A, and decaying to zero.

In this case, the symmetrical short-circuit breaking current I_b is smaller than the initial symmetrical short-circuit current I''_k. Normally the steady-state short-circuit current I_k is smaller than the symmetrical short-circuit breaking current I_b. The decaying aperiodic component i_{dc} can be calculated according to the following equation:

$$i_{dc} = \sqrt{2}\, I''_k \, e^{-(2\Pi \, f \, t \, R/X)}$$

where

I''_k is the initial symmetrical short-circuit

f is the nominal frequency

t is the time

R/X is the ratio at the short-circuit location.

For the calculation of the initial symmetrical short-circuit current I''_k, the symmetrical short-circuit breaking current I_b and the steady-state short-circuit current I_k at the short circuit location, the system may be converted into an equivalent short-circuit impedance Z_k at the short-circuit location. To calculate the peak short-circuit current, i_p, the network must first be identified as being meshed or non-meshed. The concept of meshed and non-meshed networks is dealt with in a later section of this document.

3.1.3.2.1 Initial Symmetrical Short Circuit Current

The initial symmetrical short-circuit current $I_k^{"}$ for a three-phase short-circuit with impedance Z_k at a short-circuit location is calculated as follows

$$I_k^{"} = \frac{cU_n}{\sqrt{3}Z_k}$$

The equivalent voltage source ($cU_n / \sqrt{3}$) shall be introduced at the short-circuit location. The factor c in the equation above is as defined in Table 1 or subject to the proviso of § 3.1.3.1.1.

3.1.3.2.2 Peak 3Φ Short Circuit Current in Meshed Networks

The peak short-circuit current in a meshed network is given by the following equation.

$$i_p = \kappa \sqrt{2}\, I_k^{"}$$

The term κ in the equation may be determined in one of the following ways:

a) Uniform *X/R* ratio

For this method the factor κ is determined from Figure 4, taking the largest ratio of *X/R* of all branches of the network. It is only necessary to choose the branches which carry partial short-circuit currents at the nominal voltage corresponding to the short-circuit location and branches with transformers adjacent to the short-circuit location.

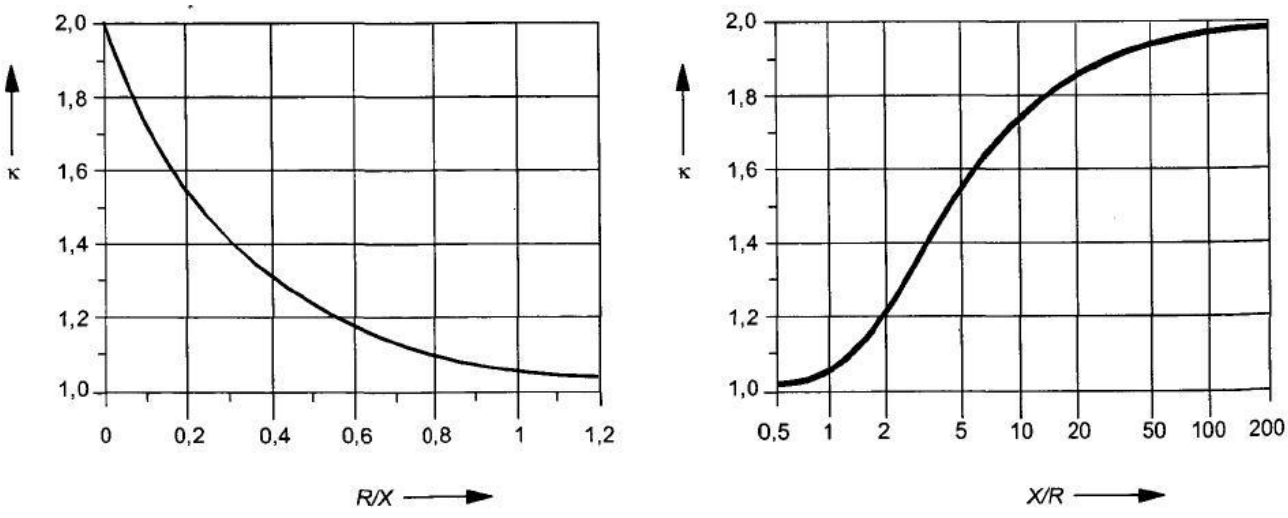

Figure 4: Factor κ for Series Circuit as a Function of *R/X* or *X/R*

b) Ratio R/X or X/R at the short-circuit location

For this method the factor κ as determined from Figure 3 is multiplied by a factor 1.15 to cover inaccuracies caused by using X_k/R_k obtained from network reduction with complex impedances. The peak current therefore becomes

$$i_p = 1.15\, \kappa \sqrt{2}\, I_k^{"}$$

If *R/X* remains smaller than 0.3 in all branches the factor 1.15 can be omitted from the calculation.

c) Equivalent frequency f_c

An equivalent impedance Z_c of the system as seen from the short-circuit location is calculated assuming a frequency of $0.4 f_{nom}$ (20Hz for a 50Hz system). The *R/X* or *X/R* ratio is then determined as follows

$$\frac{R}{X} = \frac{R_c}{X_c}\frac{f_c}{f}$$

or

$$\frac{X}{R} = \frac{X_c}{R_c}\frac{f}{f_c}$$

3.1.3.2.3 Peak 3Φ Short Circuit Current in Non-Meshed Networks

The peak short-circuit current in a non-meshed network is easier to evaluate and is generally applicable to the networks under investigation within Electrical Engineering. This current is given by

$$i_p = \kappa \sqrt{2}\, I_k^{"}$$

with $\kappa = 1.02 + 0.98 e^{-3R/X}$.

Plots of ***κ*** for different values of *R/X* and *X/R* are shown in Figure 4 above.

3.1.3.2.4 Symmetrical 3Φ Short-Circuit Breaking Current I_b

a. Far From Generator Short-Circuit

For a far from generator fault, defined according to IEC 60909-0, $I_b = I_k^{"}$

b. Near To Generator Short-Circuit

In the case of a single generator fed short-circuit or a short-circuit fed from a non-meshed network the decay to the symmetrical short-circuit breaking current is taken into account by the factor *μ* according to:

$$I_b = \mu\, I_k^{"}.$$

This factor *μ* depends on the minimum time delay t_{min} and the ratio $I_{kG}^{"} / I_{rG}$, where I_{rG} is the rated generator current. If the generator has a static exciter the minimum time delay used is less than 0.25s and the maximum excitation voltage is less than 1.6 times rated load excitation voltage.

When there is a unit transformer between the generator and the short-circuit location, the partial short-circuit current $I_{kS}^{"}$ at the high voltage side shall be transferred by the rated transformation ratio to the terminal of the generator $I_{kG}^{"} = t_r\, I_{kS}^{"}$ before calculating *μ* with the following equations:

$$\mu = 0.84 + 0.26e^{-0.26 I''_{kG}/I_{rG}} \quad for \quad t_{min} = 0.02s$$

$$\mu = 0.71 + 0.51e^{-0.30 I''_{kG}/I_{rG}} \quad for \quad t_{min} = 0.05s$$

$$\mu = 0.62 + 0.72e^{-0.32 I''_{kG}/I_{rG}} \quad for \quad t_{min} = 0.1s$$

$$\mu = 0.56 + 0.94e^{-0.38 I''_{kG}/I_{rG}} \quad for \quad t_{min} \geq 0.25s$$

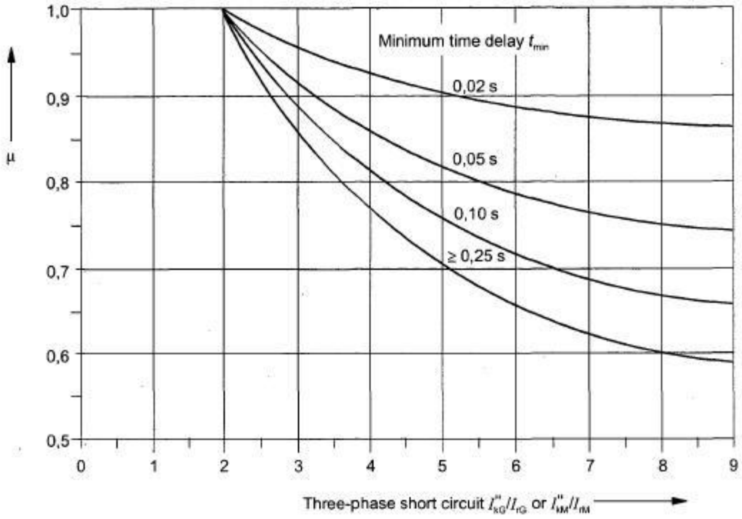

Figure 5: Factor *μ* for Calculation of Short-Circuit Breaking Current

Figure 5 above shows the value of *μ* plotted as a function of I''_{kG}/I_{rG} and t_{min}. For other values of minimum time delay, linear interpolation between curves is acceptable. The same method may be used to calculate the breaking current contribution of induction machines if I''_{kG}/I_{rG} is replaced by I''_{kM}/I_{rM} in the equation for *μ*.

c. 3Φ Short-Circuit In Non-Meshed Networks

Consider the example of a non-meshed network shown in the following figure

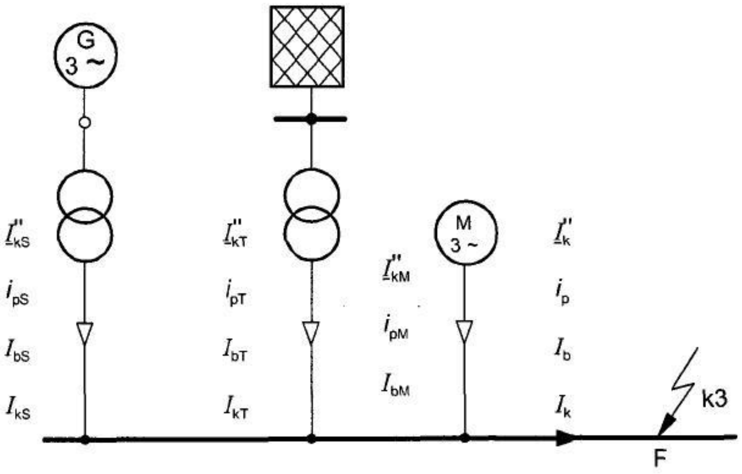

Figure 6: Example of a Non-Meshed Network

For three-phase short-circuits in networks of the type described above, the symmetrical breaking current at the short-circuit location can be calculated by the summation of the individual breaking contributions:

$$I_b = \sum_i I_{bi}$$

For the example network above this resolves to

$$I_b = I_{bS} + I_{bT} + I_{bM} = \mu I''_{kS} + I''_{kT} + \mu q I''_{kM}$$

I''_{kS}, I''_{kT} *and* I''_{kM} are taken as the contributions to I''_k at the short-circuit location. The factor q introduced into the equation for the term describing the breaking current contribution from the asynchronous machine may be determined as a function of the minimum time delay, t_{min}

$$q = 1.03 + 0.12\ln(P_{rM} / p) \qquad for \quad t_{\min} = 0.02s$$
$$q = 0.79 + 0.12\ln(P_{rM} / p) \qquad for \quad t_{\min} = 0.05s$$
$$q = 0.57 + 0.12\ln(P_{rM} / p) \qquad for \quad t_{\min} = 0.1s$$
$$q = 0.26 + 0.10\ln(P_{rM} / p) \qquad for \quad t_{\min} \geq 0.25s$$

P_{rM} is the rated active power in MW, *p* is the number of pairs of poles of the motor.

Throughout the discussion of the IEC method it is evident that there is substantial conservatism applied in the approach to fault current calculations. A clear definition when dealing with the fast decaying AC component of fault current associated with induction motor contributions is also lacking. The next section presents a realistic example and applies the methods discussed thus far and further compares these to simulation results produced by DigSilent and PSCAD/EMTDC.

3.2 CASE STUDY

The example network chosen is part of the Medupi coal power station MV network. The sample system shown in Figure 7 below neglects the effects of non-rotating loads on the secondary windings of the unit transformer. The board with the two EFP's is chosen for investigation in this exercise with particular attention paid to the contribution from the EFP's to the fault current.

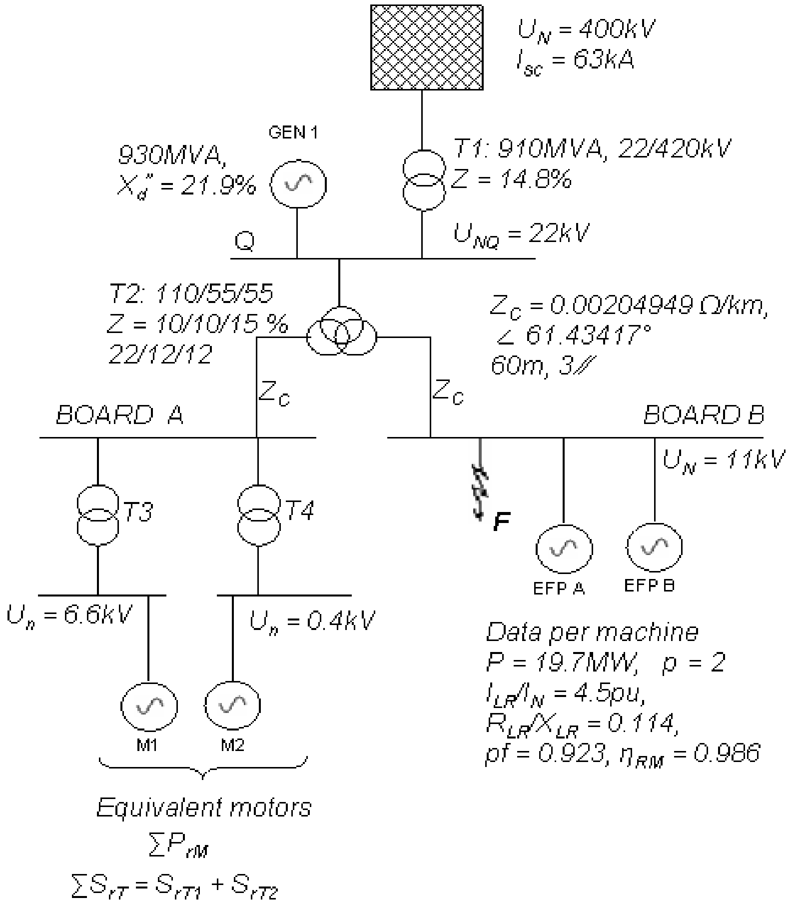

Figure 7: Sample Study Network

The first part of this exercise involves calculating the fault current contribution of the network supplying the three winding transformer up to and including the end of the cable supplying the EFP board (Board B). The impedance calculations are described in the following sections

3.2.1 Short Circuit Impedances of Electrical Equipment

3.2.1.1 Network Feeder

$$Z_{n/work} = \frac{1.1*400}{\sqrt{3}*63}*\frac{1}{t_r^2} = 4.03*\left(\frac{22}{420}\right)^2 = 1.1057x10^{-2}\Omega$$

$$X_{n/work} = \frac{Z}{\sqrt{1+(R/X)^2}} = \frac{1.1057x10^{-2}}{\sqrt{1+(0.05)^2}} = 1.1044x10^{-2}\Omega$$

$$R_{n/work} = 0.05*X_{n/work} = 5.5218x10^{-4}\Omega$$

3.2.1.2 Generator

$$Z_{gen} = K_G * 0.219 * \frac{22^2}{930} = 0.11238\Omega,$$

$$K_G = \frac{c_{max}}{1 + x_d'' \sin(\varphi_{rG})} = \frac{1.1}{1 + 0.219 * \sin(31.79°)} = 0.986$$

3.2.1.3 Generator Transformer - T1

$$Z_{T1LV} = 0.148 * \frac{22^2}{910} = 7.8716x10^{-2}\Omega$$

$$R_{T1LV} = P_{loss} * \frac{U_{rTLV}^2}{S_{rT}^2} = (0.5MW) * \frac{22^2}{910^2} = 2.9224 * 10^{-4}\Omega$$

$$X_{T1LV} = 7.8716x10^{-2}\Omega$$

3.2.1.4 Unit Transformer – T2

$$Z_{HV-MV1} = \left[\frac{0.1091}{100} + j\frac{9.2494}{100}\right] * \frac{12^2}{55} = 0.002856 + j0.24216 \quad (24)$$

$$Z_{HV-MV2} = Z_{HV-MV1}$$

$$Z_{MV1-MV2} = \left[\frac{0.09091}{100} + j\frac{14.9997}{100}\right] * \frac{12^2}{55} = 0.23802x10^{-2} + j0.39272$$

3.2.1.4.1 Impedance Correction Factors – T1

$$K_{HV-MV1} = K_{HV-MV2} = 0.95\frac{c_{max}}{1 + 0.6 * 0.0925} = 0.99005$$

$$K_{MV1-MV2} = 0.95\frac{c_{max}}{1 + 0.6 * 0.15} = 0.959$$

$$Z_{Ac} = \frac{1}{2}\left(K_{HV-MV1}Z_{HV-MV1} + K_{HV-MV2}Z_{HV-MV2} - K_{MV1-MV2}Z_{MV1-MV2}\right) = 0.001686 + j0.0514$$

$$Z_{Bc} = \frac{1}{2}\left(K_{MV1-MV2}Z_{MV1-MV2} + K_{HV-MV1}Z_{HV-MV1} - K_{HV-MV2}Z_{HV-MV2}\right) = 0.001141 + j0.18831$$

$$Z_{Cc} = \frac{1}{2}\left(K_{HV-MV2}Z_{HV-MV2} + K_{MV1-MV2}Z_{MV1-MV2} - K_{HV-MV1}Z_{HV-MV1}\right) = 0.001141 + j0.18831$$

3.2.1.5 Cable

$$Zc = \frac{1}{3}\left(0.049 + j0.09\right) * 0.06 = 0.00098 + j0.0018$$

3.2.1.6 Induction Machines – EFP A & B

$R_M/X_M = 0.1$; $X_M = 0.995*Z_M$

$$Z_m = \frac{1}{I_{LR}/I_N} x \frac{U_{RM}^2}{S_{RM}} = \frac{1}{4.5} x \frac{(11kV)^2}{21.65MVA} = 1.242\Omega = (0.1236 + j1.2358)\Omega$$

$$S_{RM} = P_{RM} / (\cos(\varphi_{RM})\eta_{RM})$$

$$I''_{kM} = \frac{1.1*11}{\sqrt{3}*1.242} = 5.625kA$$

$$I_{FL} = \frac{21.65}{\sqrt{3}*11} = 1.136kA$$

3.2.2 Fault Impedance at the Unit Board

As an intermediate step the impedance at the HV terminals of the three winding unit transformer is given by:

$$Z_{HVT} = \left[\frac{1}{Z_{gen}} + \frac{1}{Z_{T1LV} + Z_{N/W-T1LV}}\right]^{-1}$$

$$= \left[\frac{1}{j0.11238} + \frac{1}{(2.9224x10^{-4} + j7.8716x10^{-2}) + (0.055218x10^{-2} + j1.1043x10^{-2})}\right]^{-1}$$

$$Z_{HVT} = (2.61x10^{-4} + j4.9903x10^{-2})$$

At the 11kV unit board the fault impedance is given by:

$$Z = Z_{Bc} + Z_{Ac} + Z_{HVT} / n^2 + Z_{cable} = \left|(2.9047x10^{-3} + j0.25456)\right| = 0.2564\Omega$$

$$I^{"}_{k-n/w} = \frac{1.1*11}{\sqrt{3}*0.2564} = 27.25kA$$

If all equipment impedance correction factors are neglected and retaining C_{max} = 1.1 the fault current is $I^{"}_{k-n/w} = 25.752kA$.

3.2.2.1 Including the Contributions from Induction Machines

3.2.2.1.1 IEC Method

If the effect of the two EFP's is included in the initial symmetric current this becomes

$$I^{"}_{k} = I^{"}_{k-n/w} + I^{"}_{kM} = 27.25 + 2*5.625 = 38.5kA$$

The peak short circuit current can be found as follows:

$$i_{p-n/w} = \kappa\sqrt{2} * I^{"}_{k-n/w} = 2.47*27.25 = 67.31kA$$

$$\kappa = 1.02 + 0.98e^{-3R/X} \quad ;(R/X) = 0.1$$

$$i_{pM} = \kappa\sqrt{2} * I^{"}_{kM} = 13.923kA$$

$$i_p = i_{p-n/w} + 2*i_{pM} = 95.11kA$$

The breaking current can be determined from

$$\begin{aligned} I_b &= I_{b-n/w} + I_{bM} = I^{"}_{k-n/w} + \mu_M q_M I^{"}_{kM} \\ &= 27.25 + 0.791*0.844*11.25 \\ &= 34.76kA \end{aligned}$$

μ and q are calculated for a minimum time delay of 0.1s using the formulae presented earlier in this document resulting in μ = 0.791 and q = 0.844. These results compare well with those produced by DigSilent which is included in Appendix A.

3.2.2.1.2 Exponential Decaying Motor Contributions

This solution is based on the discussion presented in [[7]]. The primary contribution from the secondary winding of the unit transformer, at Board A in Figure 7, is assumed to have no AC decay. Any DC component is assumed to decay exponentially with a single time constant. Using the fault impedance at Board B, calculated previously and temporarily retaining the factor C_{max}, the symmetrical RMS current (AC component) is again given by:

$$I_s \frac{1.1*11}{\sqrt{3}*0.2564} = 27.25kA$$

The DC component of the source with, *t* in cycles is given by:

$$I_s(dc,t) = \sqrt{2} * I_s * e^{-(2*\Pi*t/(X/R)}$$

The value at the first half cycle is $I_s(dc, 0.5\sim) = 36.75kA$ and for the 5 cycle breaking time is $I_s(dc, 5\sim) = 23.94kA$. The X/R ratio is determined from the complex fault impedance in §3.2.2 and is 66.

The initial symmetrical RMS current contribution from one machine, $I_m(0)$, as determined in §3.2.1.6 is *5.625kA*. The AC component of the motor contribution decays from this initial value with time constant $T_d^{''}$ (eq 5). The expression for the a.c current as a function of time is

$$I_m(t) = I_m(0) * e^{-(2*\Pi*t/T_d^{''})}$$

The RMS symmetrical motor contribution from both EFP's to the peak-making current at *t* = ½ cycle, is $I_m(0.5\sim) = 7.86kA$ and to the breaking current at *t* = 5 cycles (100msec), is $I_m(5\sim) = 0.313kA$. The DC component of the motor contribution, with T_a = 56.6, is given by

$$I_m(dc, t) = I_m(0)\sqrt{2} * e^{-(2*\Pi*t/T_a)}$$

The DC contribution to the peak making current, at t = ½ cycle is $I_m(dc, 0.5\sim) = 15.051kA$ and to the breaking current at t = 5 cycles, is $I_m(dc, 5\sim) = 9.133kA$

The total current is found by summing the individual contributions to the a.c and d.c components and taking the square root of the sum of the squares. The peak making current is therefore given by

$$I_{sym,peak} = I_s(0.5\sim) + I_m(0.5\sim)$$
$$= 27.25 + 7.86 = 35.11kA$$

$$I_{dc,peak} = I_s(dc, 0.5\sim) + I_m(dc, 0.5\sim)$$
$$= 36.75 + 15.051 = 51.801kA$$

This gives a peak asymmetric current

$$I_{asym,peak} = \sqrt{I_{sym}^2 + I_{dc}^2} = 62.578kA$$

In a similar manner the breaking current is found to be

$$I_{sym,break} = I_s(5\sim) + I_m(5\sim)$$
$$= 27.25 + 0.313 = 27.56kA$$

$$I_{dc,peak} = I_s(dc, 5\sim) + I_m(dc, 5\sim)$$
$$= 23.94 + 9.133 = 33.07kA$$

$$I_{asym,break} = \sqrt{I_{sym,break}^2 + I_{dc,break}^2} = 43.049kA$$

3.2.3 Time Domain Simulation Results

In order to further illustrate some areas of interest presented in the discussion of the previous sections a sample network was implemented using a time domain simulation software package, PSCAD/EMTDC. The network used is essentially the same as shown in Figure 7 with the exception that the three winding unit transformer is modelled as a two winding transformer and the impedances are taken as nominal for all equipment. The objective is to illustrate the behaviour of the fault current from the various sources, with particular attention to the contribution from the induction machines, during a time domain analysis. The source is considered to be quite stiff to illustrate the limitation on fault current imposed by the transformer impedance. The following figure illustrates the network as implemented in PSCAD/EMTDC:

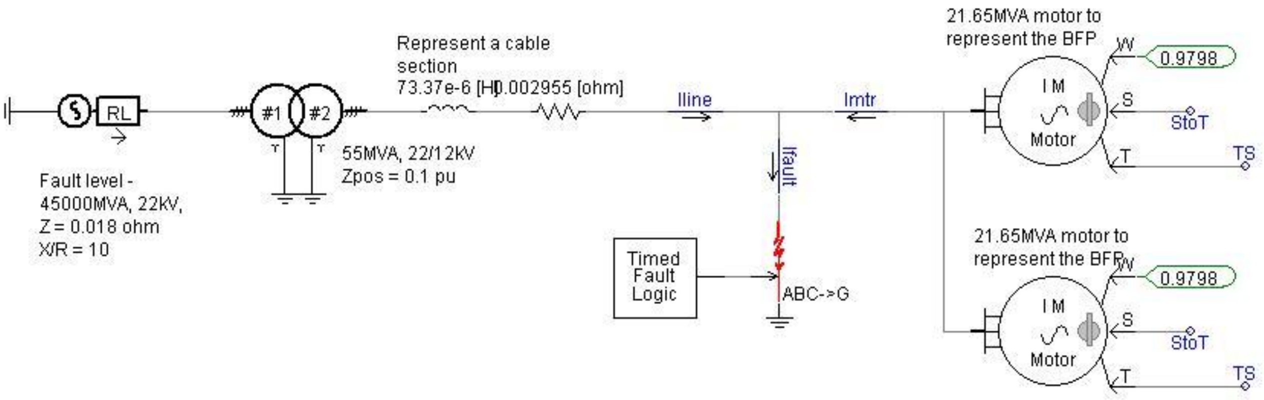

Figure 8: PSCAD Study Network

A bolted three phase to ground fault was initiated at location *F* in Figure 8 at time t = 0.5s and maintained through to the end of the simulation. Figure 9 shows the various components of the total fault current in Phase A at point F. The current in all three phases from the induction machines are shown in Figure 10.

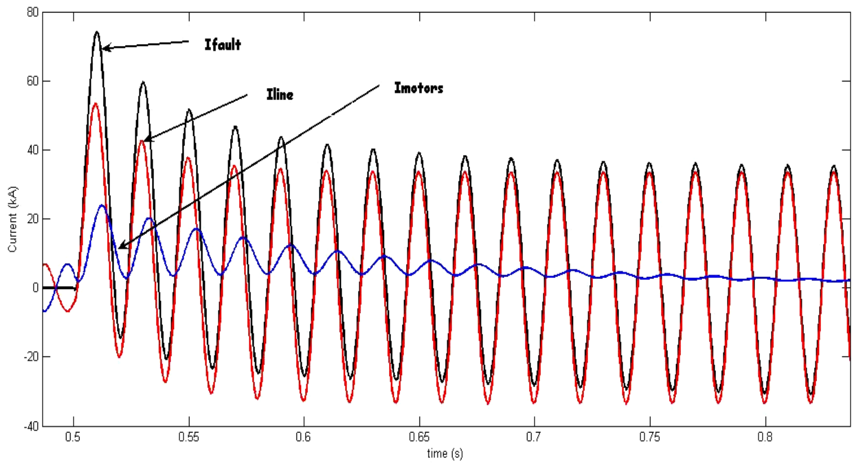

Figure 9: Fault Current in Phase A – Total, Network, Motors

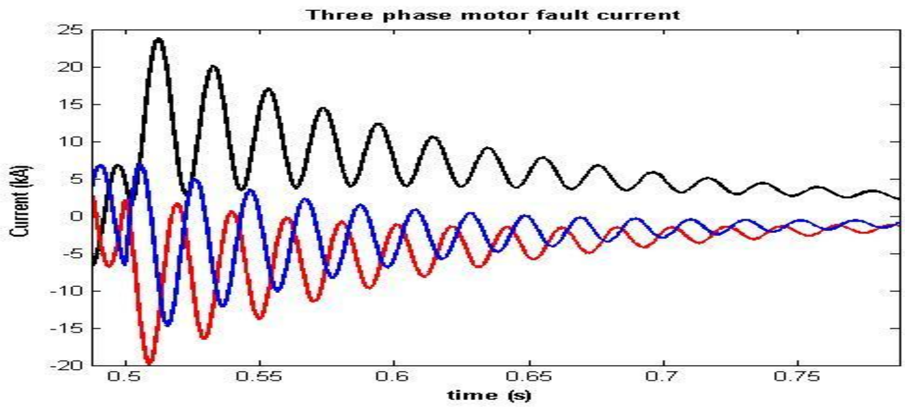

Figure 10: Induction Motor Fault Currents

Figures 9 and 10 give an indication of the expected behaviour of the fault currents viewed in the time domain. The decay time appears longer than it actually is due to the high *X/R* ratio that is modelled in accordance with the DigSilent data. As is evident from Figure 9, the fault current contribution from the motor decays rapidly in agreement with the discussion presented in §3.1.1.

3.3 ANALYSIS OF RESULTS

3.3.1 Shortcomings of the Current IEC Approach

The current approach to fault calculations and switch-gear rating relies completely on the results produced by DigSilent which directly implements the IEC standard. The inherent impedance correction factors during the simulation are not controllable or adjustable and are applied automatically as dictated by the standard and illustrated in §3.2.1. The results in §3.2.2 show the impact of the impedance correction factor on the initial symmetric fault current contribution from the network. The impedance used for equipment in the case study of §3.2.1 is taken as the minimum acceptable as provided by the manufacturer in terms of the contractual agreement. The IEC document is unclear on the exact requirement for the further impedance correction factors and they cannot be removed from the calculation in DigSilent. It is prudent to retain these to account for any possibility of errors during modelling. The second item of concern is the so-called voltage multiplication factor which is taken arbitrarily as C_{max} = 1.1 according to Table 1. The IEC standard states that the values listed in Table 1 should be used in the absence of a local standard governing the allowable voltage levels. With the factor currently used the pre-fault voltage at the faulted bus equates to *V = 12.1kV*, assuming a nominal voltage of *11kV*. This voltage is excessive as ESKOM have standards in place governing the maximum allowable voltage at each voltage level.

Another extremely important issue is the modelling of the system and equipment *X/R* ratio. This factor has a direct impact on the decay rate of transients and should be corrected. An example is the modelling of the unit transformer which indicates winding losses of approximately 60kW. This results in an extremely large *X/R* ratio of the transformer and therefore the fault impedance.

The final and most contentious issue is the approach to dealing with fault current contributions from induction machines. The IEC method is very conservative in it's approach and does not deal with the fast a.c decay phenomenon adequately. It caters for the change in current by introducing multiplication factors. A discussion on the salient points surrounding this topic is presented in §3.1.1. Another common approach in dealing with the contribution from induction machines is to exclude the pre-fault load current from the calculation for fault current contribution. This is based on the assumption that the load current is small in comparison to the fault current generated by machine. This is not true in this case as the ratio of I_{LR} / I_{Fl} of the EFP's is 4.5, and remains true for all cases where the ratio of starting to full load current is small.

Table 2 below presents a comparison of the breaking current for a selected time span to illustrate the differences in the motor current as the fault progresses for the IEC method and that presented in [[7].]

Table 2: Comparison of Breaking Currents

t sec)	**IEC (t (s))**	**REF 7 (t (cycles))**
0.02 (= 1cycle)	40.77	32.75
0.04	40.77	29.93
0.06	37.34	28.56
0.08	37.34	27.89
0.1	34.77	27.56

3.4 RECOMMENDATIONS

The following recommendations are made:

a. Retain the approach to using the minimum acceptable impedances for equipment in the DigSilent simulation and the implicit impedance correction factors

b. Retain a *c* factor of 1.1 to incorporate an adequate safety margin in the calculation

c. Use the correct X/R ratio for all equipment during the modelling exercise.

d. Perform the fault study in DigSilent without any motor contribution and address the motor contribution using the approach presented in §3.2.2.1.2 to verify the impact of the motors. The initial symmetrical fault current contribution from the motors should be reduced by the load current drawn at the instant of fault inception.

3.5 CONCLUSIONS

Comparison of the three results indicates that the IEC method for fault current calculation is the most conservative. If the recommendations of the previous section are implemented the rating of the required breaker will be correctly determined with the motor contribution taken into account. The specification of the breaker as illustrated in the document should be equal to or greater than the symmetrical short-circuit current calculated at the breaking time. The second consideration is the peak-making current. Once the breaker is selected it must be confirmed that the associated peak-making capability of the breaker is greater than the peak-making current calculated using [[7]]. This corresponds to the value calculated in equation 29 of this document. This essentially implies that a 31.5kA breaker will suffice for the study case considered in §3.2.

4. AUTHORISATION

This document has been seen and accepted by:

Name & Surname	Designation
	Document Approved by TDAC ROD 13 March 2013

5. REVISIONS

Date	Rev.	Compiler	Remarks
November 2012	0	P.I. Heera Senior Electrical Engineer.	Draft document for Review created from N.PPZ 45-940
May 2013	1	P.I. Heera	Final Document for Publication

6. DEVELOPMENT TEAM

The following people were involved in the development of this document:

- None

7. ACKNOWLEDGEMENTS

- None

APPENDIX A: DIGSILENT RESULTS FOR THE NETWORK OF FIGURE 7

```
|                  |                                                                |   DIgSILENT    | Project:
|                  |                                                                | PowerFactory   |-----------------------
|                  |                                                                |    14.0.510    | Date:  3/1/2009
|

| Fault Locations with Feeders
| Short-Circuit Calculation according to IEC                    3-Phase Short-Circuit/ Max. Short-Circuit Currents |

| Asynchronous Motors                      | Grid Identification                      | Short-Circuit Duration
|    Always Considered                     |    Automatic                             |    Break Time                    0.10 s
|                                          |                                          |    Fault Clearing Time (Ith)     0.10 s
| Decaying Aperiodic Component (idc)       | Conductor Temperature                    | c-Voltage Factor
|    Using Method                B         |    User Defined              No          |    User Defined                  Yes
|                                          |                                          |    c-Factor                      1.10    |

| Grid: Unit 1              System Stage: 110_55_55_10%Z_ |                                        | Annex:           / 1
```

	rtd.V. [kV]	Voltage [kV]	Voltage [deg]	c-Factor	Sk" [MVA/MVA]	Ik" [kA/kA]	Ik" [deg]	ip [kA/kA]	Ib [kA]	Sb [MVA]	Ik [kA]	Ith [kA]
11kV Unit Bd	11.00	0.00	0.00	1.10	731.89 MVA	38.41 kA	-87.53	102.26 kA	34.58	658.83	26.36	49.86
BFP 20					106.92 MVA	5.61 kA	96.58	14.94 kA				
BFP 30					106.92 MVA	5.61 kA	96.58	14.94 kA				
Unit Trfr Bd 2 LV					518.83 MVA	27.23 kA	90.78	72.49 kA				