A COMPARISON OF SHORT CIRCUIT CALCULATION METHODS AND GUIDELINES FOR DISTRIBUTION NETWORKS

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ABSTRACT

The paper focuses on several different short-circuit calculation methods and standards/guidelines. Special attention is paid to modelling enhancements of a typical steady state short circuit calculation to take into account the impact of AC and DC decay. Several networks were used to test these enhancements and the findings are summarised on a representative section of a genuine distribution network in the UK.

INTRODUCTION

Short-circuit calculations (SCCs) are one of the most important tasks undertaken in power system planning and operation. Switchgear selection, protection settings and coordination require comprehensive, detailed and accurate SCCs. A significant effort has been made by engineers and academics to improve the SCC methods and compile the SCC standards and guidelines to be more suitable for industrial applications.

SCCs have been subject historically to significant approximations mainly to lessen the computational burden and reduce the input data requirements. In terms of computational time, the steady-state SCCs are significantly faster then dynamic transient or electromagnetic simulations. However, the steady-state SCCs often fail to correctly calculate the AC and DC decay resulting from rotating machines. Therefore, various enhancements of the steady-state SCC method have been applied to improve the representations of rotating machines. They range in complexity from simple corrections of sequence impedances, to the utilisation of sub-transient and transient impedances and short-circuit (SC) time constants for rotating machines. The influences of some of these modelling enhancements are discussed in this paper.

The paper focuses on the modelling enhancements found in the literature and the following two SCC standards: the North American ANSI/IEEE standard 141 and its European counterpart IEC 60909.

Special attention has been paid to the selection of a set of genuine distribution networks for comparisons of the suggested enhancements. Due to space limitations and for the sake of simplicity and brevity the paper focuses on the results obtained for a representative section of a genuine distribution network.

SHORT-CIRCUIT CALCULATION METHODS AND STANDARDS/GUIDELINES

Short-circuit calculation methods

Non-decaying short-circuit calculation method

A steady-state non-decaying SCC is based on the superposition method where the fault currents, fault voltages and fault flows are calculated using the following two networks:

- N1 the active pre-fault network and,
- N2 the passive pre-fault network where a voltage source is introduced at the fault point. The voltage source ensures the same pre-fault voltage at fault point with respect to the pre-fault conditions, but in opposite direction.

Combining these two networks (N1 & N2) using the superposition method one can obtain the faulted network. Considering that the pre-fault conditions are often known from the load flow calculation, additional calculations are not required for the N1 network. However, to calculate the fault current, a Thevenin equivalent of the N2 network as seen from the fault point needs to be determined. This equivalent consists of a known voltage source and equivalent unknown impedance seen from the fault point (driving point impedance -DPI).

Considering that the N2 network has only one voltage source its busbar voltages can be easily determined from the fault current. Adding these voltages to the pre-fault voltages of the N1 network, one can calculate the fault busbar voltages and fault flows.

The calculation uses fixed impedances for rotating machines and it has low computational demands and input data requirements (see Fig.1.). The computation objective is to determine the inverse network admittance matrix to determine DPI, and to carry out a backward-forward solution to determine the N2 network voltages. [1]

A typical fixed impedance short-circuit calculation

A fixed impedance calculation (FIC) uses the superposition method described above to calculate:

- C1 The initial sub-transient symmetrical short-circuit current I''_{sym} and,
- C2 The transient symmetrical short-circuit current I'_{sym}.

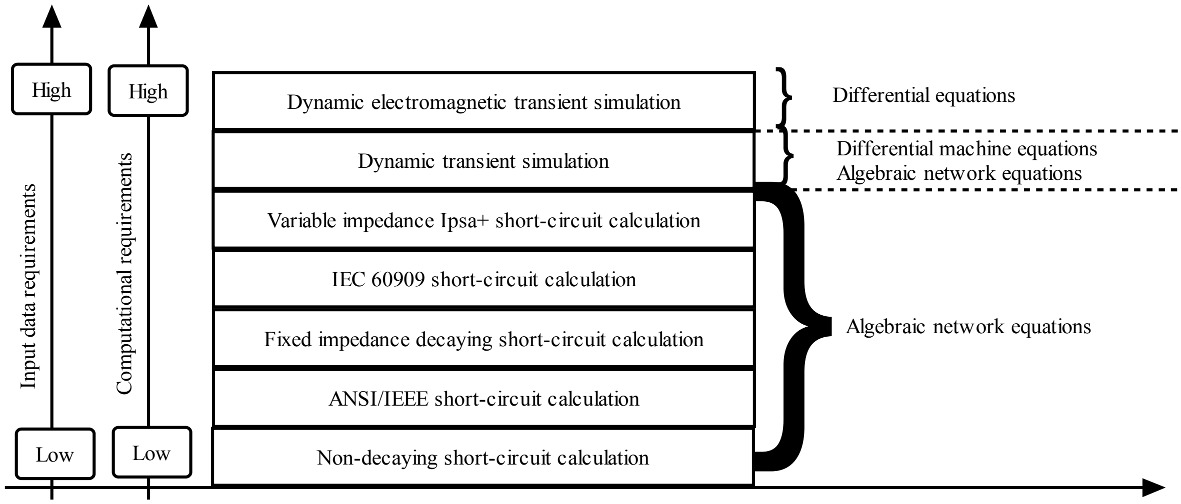

Figure 1-Short-circuit calculations

FIC modelling enhancements are related to the calculation of RMS SC break current, Peak SC current and DC SC current. The FIC calculation assumes that the sub-transient current components decay to negligible values within 120 ms (a time constant of 40 ms). The RMS symmetrical short-circuit current at the break time t_b (ms) can be calculated using the following equation:

$$I_{sym}^{t_b} = I_{sym}^{'} + (I_{sym}^{''} - I_{sym}^{'})e^{-t_b/40}. \quad (1).$$

The FIC calculation of the peak short-circuit current is based on the following equation:

$$I_{peak} = \sqrt{2}I_{sym}^{''}(1.02 + 0.98e^{-3R/X}), \quad (2)$$

where the R/X ratio is obtained using the IEC60909 equivalent frequency method called Method C.

Method C is a simple re-calculation of the DPI of the N2 network. In this re-calculation all network inductive and capacitive reactances needs to be scaled to an equivalent frequency f_c (less than nominal frequency). The applied equivalent frequency f_c depends on the time elapsed from the instant of fault. The re-calculated R/X ratio of DPI of the N2 network needs to be scaled back to the nominal frequency and then used in the equation above.

The same R/X ratio can be used to calculate DC SC component using the following equation:

$$I_{dc} = \sqrt{2}I_{sym}^{''} * e^{-2\pi\times 50\times t_b\times R/X}. \quad (3)$$

In terms of computational efforts (see Fig.1) FIC requires an additional inverse matrix calculation (with respect to the non-decaying method described above) to re-calculate the R/X ratio using Method C.

Variable impedance short-circuit calculation method

Two most important modelling enhancements of the variable impedance SCC method as used in IPSA+, are the use of non-fixed impedances for rotating machines and separate calculations of AC and DC SC components.

In reality, the effective machine impedances vary with the time elapsed from the instant of the fault. The calculation of these impedances is described in [2] in more detail. Therefore, when calculating the symmetrical AC SC component, both open and short-circuit circuit time constants and the d and q axis sub-transient, transient and synchronous reactances are used to calculate machine impedances. Similarly, the armature time constants and d and q axis sub-transient reactances are used to calculate time varying machine impedances for the calculation of the DC SC component.

In the applied procedure for the calculation of the machine impedances, special attention is devoted to the calculation of effective "external" network impedances seen by each machine [2]. For a remote fault involving external impedances between the machine and the fault point, the effective machine reactances are increased by the value of this external reactance. The IPSA+ SCC uses open circuit time constants and the external impedance to re-calculate the true machine short-circuit time constants.

Also in contrast, the peak current value in this approach is determined using the following equation:

$$I_{peak} = \sqrt{2}I_{sym}^{10ms} + I_{dc}^{10ms}, \quad (4)$$

where I_{sym}^{10ms} is the symmetrical AC SC component at 10 ms after the fault.

In terms of computational efforts this method is the most demanding steady-state SC calculation discussed in this paper. This is because the calculation of the external impedances is in essence an iterative calculation of DPI [2]. Moreover, the separate calculations of AC and DC SC components duplicate the computational efforts with respect to the non-decaying SCC (see Fig.1).

Short-circuit calculation standards/guidelines

ANSI/IEEE short-circuit calculation

ANSI/IEEE 141 is a North American standard for SCCs. The standard gives detailed guidelines on the SCC methodology and data requirements. This SCC is one of the simplest steady-state SCC in terms of the computational requirements.

The machine impedances used for the calculation of DPI are mainly sub-transient reactances scaled using impedance correction factors. These correction factors are different for different machines (size and type) and for the calculations of momentary and interrupting duties. The standard assumes unloaded network conditions, which means that the pre-fault load flow calculation for the N1 network is not required [3].

The peak SC components can be calculated multiplying the initial momentary SC current by a crest factor of 2.7 [3]. AC and DC decaying are encountered through use of the specified decrement factors. These factors depend on the X/R ratio of the driving point impedance and the circuit breaker contact parting time. They are different for near-to and far-from generators faults [3].

IEC 60909 short-circuit calculation

IEC 60909 [4] is a predominantly European used SCC standard. The SCC method is similar to the FIC calculation described above. The most importance differences are the use of a voltage correction factors (*c*=1.1 for high-voltage networks) and impedance correction factors.

The introduction of the voltage correction factor *c* basically increases the voltage magnitude of the voltage source applied to the passive network N2 by 10%. This makes the fault current at least 10% higher and sometimes leads to more conservative (pessimistic) results.

The impedances of all rotating plant are constant in this calculation. These constant impedances for synchronous machines are calculated using sub-transient impedances and the corresponding impedance correction factors. The impedances used for asynchronous motors are calculated using the locked rotor impedance values.

The calculation of Peak and the DC SC component is based on the modelling enhancements suggested in Eq.(2) and Eq.(3),respectively. It should be pointed out that except for Method C, the calculation of the X/R ratio for peak SC current can be performed using two less computationally demanding methods: Method A and B. Method A uses the highest X/R ratio of all network branches carrying short-circuit current. Method B uses the ratio of the driving point impedance. Method A is a simple but conservative method, while Method B gives acceptable results for peak make SC current, but not for determining DC SC break current components [4].

For the calculation of AC decay, IEC 60909 suggests the use of two decrement factors μ and q, which are values between 0 and 1 [4]. Multiplying these factors with the machine initial SC current ensures that an AC decay is achieved. The μ factor is used for the calculation of synchronous machine AC decays, whereas both factors are used for the calculation of asynchronous machines AC decays.

The μ factor decays exponentially with respect to the ratio of the machine initial SC current to its rated current. The smaller the value of t_b, the slower the decay of this factor. The q factor is a natural logarithm function of the rated asynchronous machine power per pole pairs. In essence, the larger this power, the faster is the machine decay. Different logarithm functions are used for different time constant values of t_b [4].

In terms of computational efforts the IEC 60909 SCC is relatively similar to the FIC method (see Fig.1), however the calculation of decrement factors especially for meshed networks [4] makes the IEC 60909 slightly more demanding.

RESULTS

It is important to note that it is not intention of this paper to criticise or endorse any of the compared SCCs calculations and standards.

To compare the results obtained using different SCCs two difficult choices had to be made:

1) Which SC quantities to compare?
2) What should be the reference for comparison?

The quantities chosen for comparison were:

- Initial symmetrical current
- RMS break current
- Peak make current
- DC current (where possible).

The variable impedance IPSA+ SCC results were used for comparison only because this type of calculation is the most demanding steady-state SCC in terms of computational and input data requirements.

The SCC comparisons were carried out for several different distribution networks. In this paper to demonstrate the findings, a representative section of 132/33/11 kV distribution network was used. This network is well meshed at the 132 kV level, weakly meshed at the 33 kV level, and radial at the 11 kV level (see Fig.2). The network has 14 buses, 4 generators (Bus 1, Bus 5, Bus 6 and Bus 14) and several asynchronous motors mainly connected at 11 kV busbars.

FIC versus variable impedance Ipsa+ SCC

The results obtained by these two SCC methods are very similar for almost all networks that were tested throughout this work on the comparison of SCCs. The results for the 132/33/11 kV weakly meshed network are shown in Fig. 2. It can be seen from Fig. 2 that there is almost no difference in initial symmetrical SC current. However, Peak make and DC SC current show large differences for Busbars 10 and 11. Bearing in mind Eq.(2) and Eq.(3) and that the initial symmetrical short-circuit current are almost identical for both calculations, the difference in the Peak make and DC component is due to different calculations of the X/R ratio. The differences in RMS asymmetric break current are also predominantly caused by these differences in DC SC current.

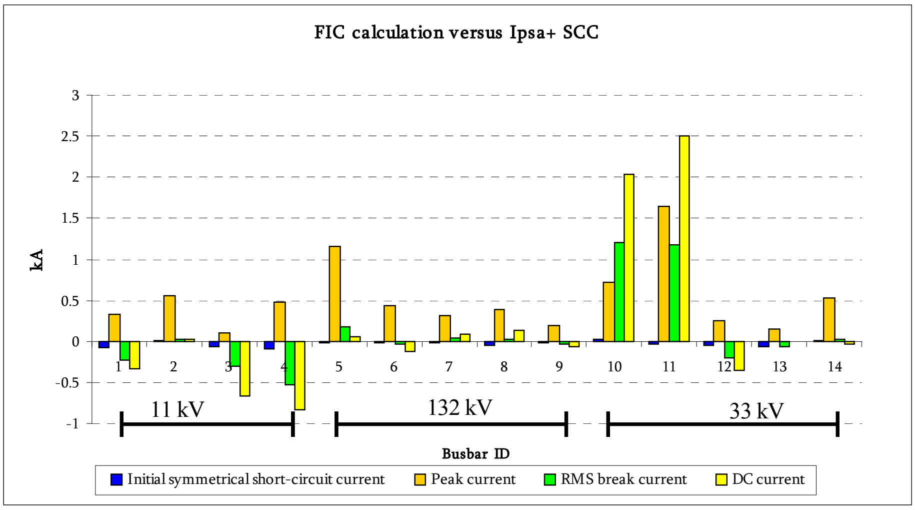

Figure 2 –FIC versus variable impedance IPSA+ SCC results

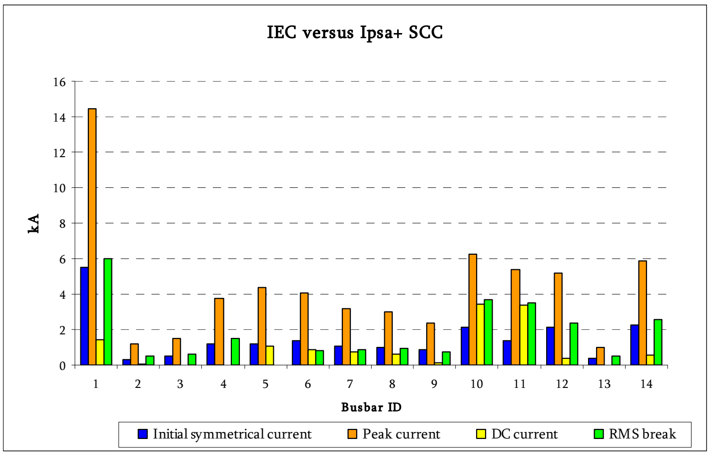

Figure 3 –IEC versus variable impedance IPSA+ SCC results

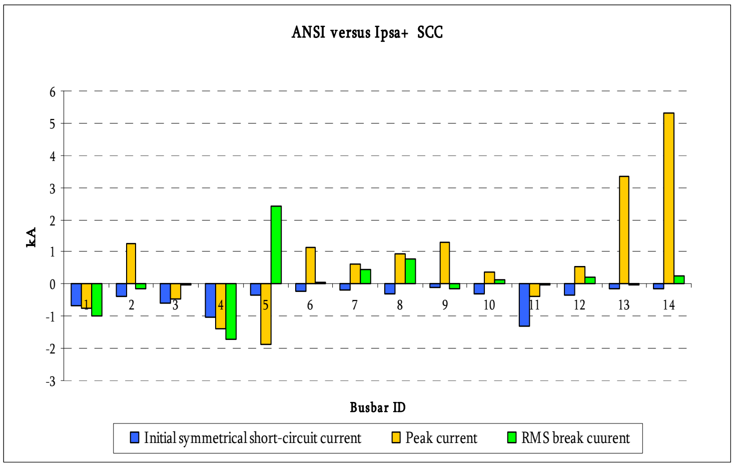

Figure 4-ANSI versus variable impedance IPSA+ SCC results

IEC versus variable impedance IPSA+ SCC

It was observed that the IEC 60909 SCC for all tested networks gave the highest SC fault levels. For example, the comparison of the IEC 60909 results with IPSA+ showed that the differences were always positive for all SC comparison quantities. The use of voltage and impedance correction factors makes the IEC 60909 method one of the most conservative SCC methods.

ANSI versus variable impedance IPSA+ SCC

The results of the ANSI/IEEE SCC are significantly influenced by the use of impedance correction factors for rotating machines. It was observed that the ANSI/IEEE SCC calculation often produced a slightly lower initial symmetrical current than IPSA+ or a FIC SCC. The ANSI peak values are often overly pessimistic for the faults where the DPI is relatively small. On the other hand for near-to-generators faults, these values can be slightly optimistic. The decrement factors used by the ANSI SCC give reasonable decays provided the X/R ratios are within the intervals specified in [3].

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