Design of a Medium Voltage Superconducting Series Reactor for a Grid-Connected Power Engineering Research Site

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INTRODUCTION: Busbar fault levels on power grids are increasing due largely to an increase in network interconnectivity and an increase in distributed generation. The superconducting fault current limiters (SFCL) is now emerging as a viable alternative to traditionally employed options namely, the installation of series air core reactors, high impedance transformers or equipment with a higher fault level rating. It is however the large initial capital cost for an SFCL that remains its main obstacle to mainstream adoption.

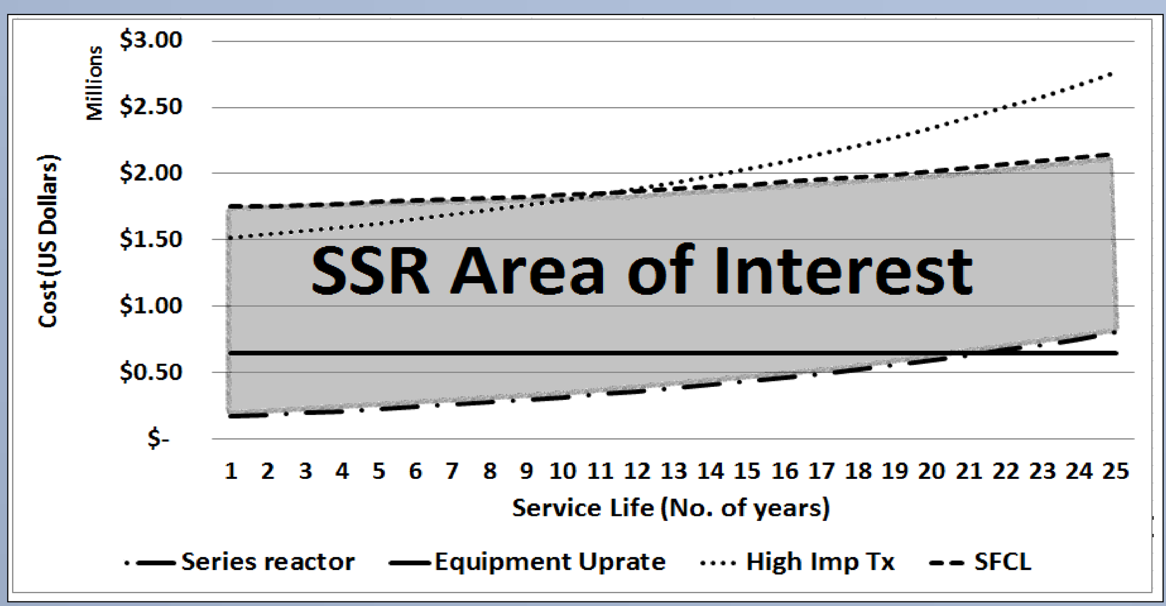

FIGURE 1. Lifecycle cost of fault management options for a case study in South Africa

As an alternative, the authors therefore propose developing a superconducting series reactor (SSR) which would achieve the desired fault level management at a reduced cost. In essence, a SSR is a superconducting coil that would replace, and thereby be more efficient, than a series air core reactor (less I^2R losses), and also utilize less superconducting material when compared to a SFCL solution. It is further proposed that the Doornkop research site is modified to enable it to be used for applied superconductivity research.

DOORNKOP RESEARCH TEST SITE: This research test site is energised at 22 kV and its main purpose is to test various public safety related protection and detection measures for the high impedance faults caused by downed conductors. The modifications include the installation of an additional 3 phase isolator , a steel cross-arm and cabling to the control room.

FIGURE 2a. Doornkop research test site

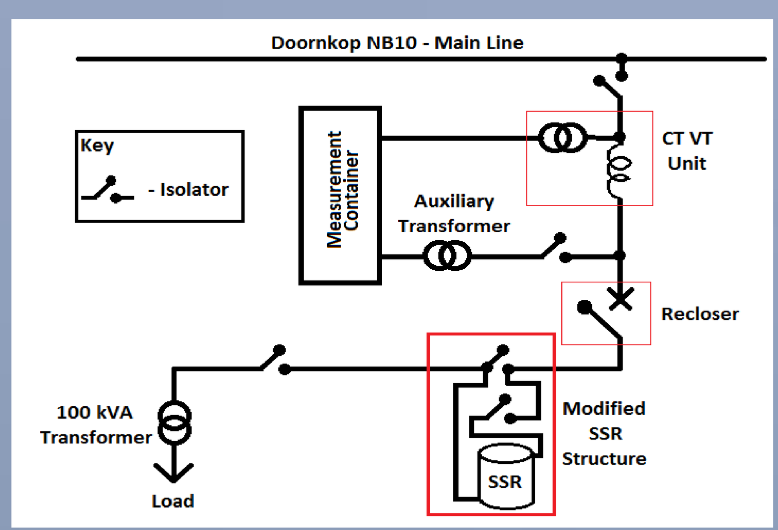

FIGURE 2b. Proposed site layout

REDUCTION OF FAULT LEVEL USING SERIES INDUCTANCE: When the desired fault current is known, the reactance required for a current limiting reactor is given in (1), where I_{SCA} and I_{SCB} represent the desired and existing short circuit current values (kA) respectively and V_{LL} represents the system voltage in kV.

$$X_{CLR} = V_{LL}\frac{\left[\left(^1/_{I_{SCA}}\right)-\left(^1/_{I_{SCB}}\right)\right]}{\sqrt{3}} \quad (1)$$

Using (1), it is determined that an inductance of 2.43 mH is required to reduce the fault level at a typical distribution substation from 25 kA to 10 kA. One of the drawbacks of testing the SSR at the research site is that the fault level is comparatively low (0.9 kA) when compared to typical substations and this results in a small reduction in fault level when the 2.43 mH reactor is installed.

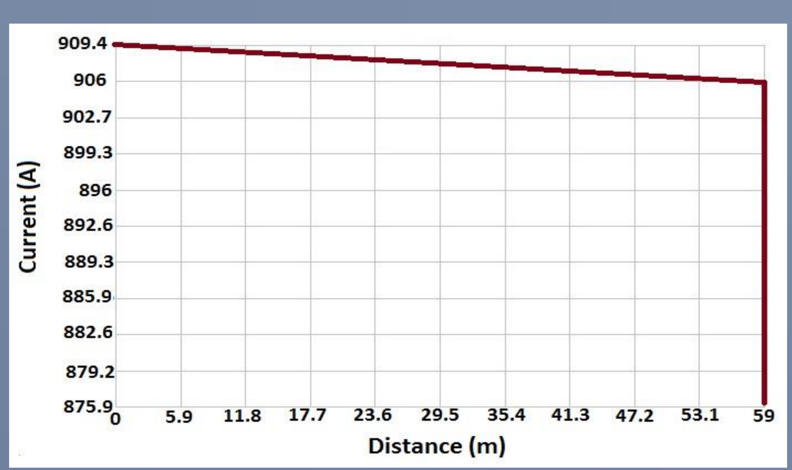

FIGURE 3. Simulated fault current plot for Doornkop NB10 confirming the reduction of fault current at the Doornkop research site after installation of a 2.43 mH SSR

SUPERCONDUCTOR SERIES REACTOR (SSR) DESIGN

Coil Design: Both the design of a thin walled solenoid and a pancake coil was considered to achieve the desired inductance. The major parameters defining a coil containing no ferromagnetic materials are shown in fig. 4. The self-inductance for the coil, *L*, is determined by (2) where $\alpha \equiv a_2/a_1$ and $\beta \equiv b/a_1$. The self-inductance for a fat pancake coil (α>>1) may be approximated using (3). For a solenoid, where β→1, the inductance parameter, $\mathcal{I}(\alpha,\beta)$, required in (2) is determined by (4), and the inductance parameter for a thin walled long solenoid ($\alpha\approx1$ and $\beta\rightarrow\infty$) reduces to (5).

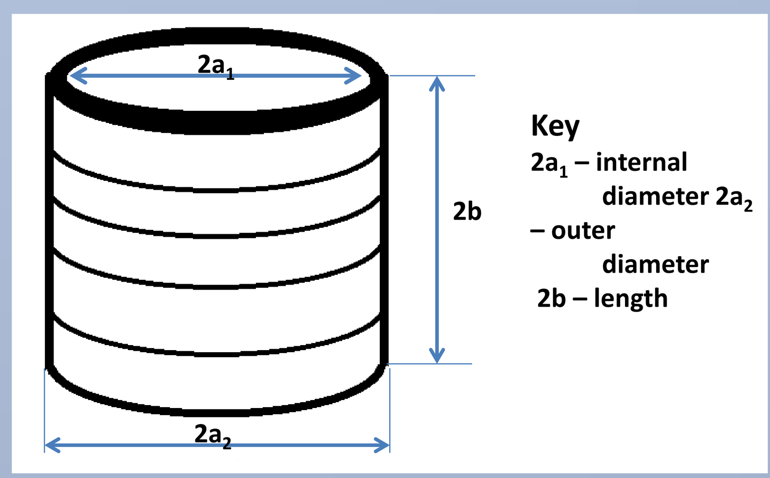

FIGURE 4. Parameters defining a coil

$$L = \mu_0 a_1 N^2 \mathcal{I}(\alpha,\beta) \quad (2)$$

$$L \approx 0.5\, \mu_0 a_2 N^2 \quad (3)$$

$$\mathcal{I}(\alpha,\beta) = \frac{\pi.\alpha}{2(\beta+0.5)} \quad (4)$$

$$\mathcal{I}(\beta) = \frac{\pi}{2\beta} \quad (5)$$

For the configurations considered the thin-walled solenoid and pancake coil yielded a maximum inductance per unit length of 13.77 µH/m and 3.64 µH/m respectively. Using the Generalized Reduced Gradient nonlinear optimization algorithm with the equation to determine self-inductance of the respective coils and practical constraints to aid in the construction of the coil, it was decided that a thin-walled solenoid will be designed for and utilized in the SSR. Table 1 gives the characteristics of the proposed superconducting coil for the SSR.

TABLE 1: Coil Characteristics for Prototype SSR

Coil Characteristic	Symbol	Value	Units
Outer Diameter	$2a_2$	0.85	m
Height	$2b$	0.86	m
Number of Turns	N	66	number
Rise of helix in 1 revolution		13	mm
Total helical length	T	176.2	m
Inductance	L	2.43	mH

Technical ratings for SSR : Since the detailed requirements and technical parameters for traditional current limiting reactors are specified in IEC 60076-6:2007, the technical parameters for the SSR is also extracted from there and summarized in Table 2.

TABLE 2: Technical Rating for Superconducting Current Limiting Reactor

Technical Requirements	Symbol	Value	Units
Maximum System Voltage	U_m	24	kV
Rated Frequency	f	50	Hz
Basic Insulation Level	BIL	150	kV
Rated Impedance	Z	0.76	Ω
Rated Inductance	L	2.43	mH
Rated Continuous Current	I_c	2.62	A
Rated Thermal Short-Circuit Current	I_{SC}	0.9	kA
Min. Nominal Creepage Distance		744	mm

The tank that houses the SSR will be manufactured from a high chromium-containing corrosion resistant stainless steel (316SS). The dimensions of the tank are determined by the insulation thickness (T_i), the coil dimensions and the dielectric breakdown strength of air ($E_{max\,(air)}$) and liquid nitrogen ($E_{max\,(LN2)}$). A *BIL* of 150 kV was used and the dimensions of the tank are therefore calculated as having a width of 112 cm and a height of 120 cm.

$$Tank_{Height} = 2(T_i) + 2a_2 + (\,2(E_{max\,(air)}) + E_{max\,(LN2)})/U_m \quad (6a)$$

$$Tank_{Width} = 2(T_i) + 2b + 2(E_{max\,(LN2)}) \quad (6b)$$

CONCLUSION: This study shows how a research site may be modified to incorporate the research and testing of applied superconducting power devices, including the SSR, which is proposed as an alternative in the management of distribution fault levels. Design parameters for the prototype SSR to be installed at the Doornkop research site has been extracted from IEC 60076-6:2007 and presented. Installing the prototype SSR at the research site will provide an opportunity to test the prototype in an environment with full control of fault parameters, and with no customer impact. However, the low continuous current at the site has necessitated a compromise by having to design for an inductance that has a small impact on the fault level at the research test site when compared to the impact that it would have at a typical substation.

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