Comparison of Superconducting Fault Current Limiters against Traditionally Employed Practices in the Management of Fault Levels in the South African National Grid

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Abstract—**Fault levels on many electrical networks are reported to be increasing and this increase is largely attributed to increasing network interconnectivity and an increase in generation. Some of the ways in which generating capacity is being increased is due to generation capacity expansion projects and localized renewable energy and co-generation projects. Utilities are therefore increasingly confronted with the scenario wherein fault levels at substations are increasing beyond the rated value of the installed equipment thereby necessitating the requirement for some form of fault level management. Traditionally, when faced with this scenario, power utilities considered one of three options: (i) Replace equipment with higher rated equipment or, (ii) Install series reactors or, (iii) Replace the existing transformers with high impedance transformers. This paper aims to compare the utilization of a superconducting fault current limiter (SFCL) against these three options as an effective fault level management device from the perspective of a power utility. Utilising fault level data from existing networks in the South African power pool, we will first contextualize the existing risk by quantifying the number of substations that require an intervention to prevent both a safety and/ or operational risk. By means of a case study, various fault level management tools would then be assessed taking into account factors not limited to only the capital cost of the installation but also the associated increase in operational and energy cost of the various options. We found that when comparing the SFCL solution to other traditional ones, the high capital cost of the SFCL outweighed the reduced operating cost over a 25 year service life and is presently not a viable alternative for fault level management in the South African power grid. This conclusion may not be globally applicable.**

Index Terms— **fault level management, power system management, superconducting fault current limiters.**

I. Introduction

Current research towards the development of a superconducting fault current limiter (SFCL) for large scale power grid applications has led to the establishment of long term pilot installations on existing power grids and test grids to prove operability and performance, for example, the recent installations at San Juan de Dios Substation in Mallorca (Spain) [1], and Icheon substation (Korea) [2]. These installations are testimony that SFCL's have now evolved to a position wherein it too may be considered as an effective means of fault level management. This paper compares, from a financial and operational perspective, high temperature superconductor tape based resistive SFCL's against traditionally power utility employed methods of fault level management on a large scale power grid.

It is often cited that busbar fault levels on power grids are continually increasing [3] and [4]. A high fault level is not intrinsically undesirable as it is an indication of the strength and robustness of a power system, but becomes so when it is larger than the rating of the installed equipment. This then requires an intervention to mitigate against the inherent operational and safety risks.

Fault levels are increasing, primarily due to network interconnectivity, in an effort to improve power delivery reliability, and an increase in generation to meet the demands of increasing growth. In South Africa, for example, the construction of Medupi and Kusile power stations, two 4,800 MW coal fired power stations, within the next four years will increase the generating capacity of the South African power pool substantially by 23 % to 50,794 MW [5]. Government initiatives has also resulted in an increase in the number of independent power producers, co-generation schemes and micro-renewable projects and this is known to increase the local generating capacity of the network and thus the fault levels.

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This paper concerns a case study that was used to investigate the impact of localized renewable energy on equipment rating exceedance and the life cycle based cost benefit analysis of various fault level management technologies.

II. Fault Level Trends in South Africa

A. Background

Eskom is one of the largest power utilities in the world, generating almost all of South Africa's electrical energy (240 642 GWh) and it is therefore responsible for the South African national grid. As of 2012, its distribution asset base comprised of over 47 509 km of distribution lines and 311 831 km of reticulation power lines making it the largest power line system on the continent of Africa [6].

An analysis of the existing busbar fault level versus the installed breaker ratings at substations on the Eskom distribution power network reveals that there are already installations where the fault level rating of the breaker is presently being exceeded. The number of substations where this occurs is predominantly to the north and interior of South Africa which is the economic hub of the country and this could be attributed to the fact that the majority of the country's generation fleet is in the same geographical area hence the higher fault levels.

There are presently 82 substations on Eskom's distribution network where it is recorded that the busbar fault level exceeds the installed network breaker rating. This represents a small component of Eskom's installed base (2.52 %) and measures have already been put in place to manage this risk. This ranges from network reconfiguration (splitting of busbars where applicable), verification of asset information to confirm rating and the uprating of equipment. The current national specification lists the fault level requirement for network breakers at 25 kA and many of the installations that are presently noncompliant have network breakers with a lower short circuit current rating than is currently specified installed that have surpassed its service life and are in need of replacement. If these network breakers are replaced with units procured against the current specification, they will be compliant.

B. Impact of increased generation

South Africa experienced a major energy crisis in 2008 where the ever increasing demand for electricity was unable to be met by the existing installed generation plants. The government responded in two ways; (i) they sanctioned the construction of two new coal fired power stations that would together increase the base-load generating capacity by 23 % and, (ii) they, via the National Energy Regulator of South Africa (NERSA), launched a series of initiatives to promote large scale renewable energy development.

The Renewable Energy Feed-In Tariff (REFIT) was first proposed which guaranteed a floor price for various renewable energy options but this was not successful for various reasons and was replaced with the Renewable Energy Bids (REBID) process [7], wherein a ceiling tariff rate is set for each technology and interested parties bid for power purchase agreements. This process has been very successful and this paper considers the potential impact of these successful power purchase agreements on the calculated fault levels at substations by simulating their impact on a typical substation that is presently equipped with equipment that is within 90% of its rating. Impact studies regarding the two new coal fired power stations (Medupi and Kusile) have been conducted by Eskom whereas the impact of localized renewable energy generation has not been sufficiently analysed owing largely to the randomness of their location. Part of this study analyses the impact of localized renewable energy projects and the effectiveness of the fault level management tools considered.

An analysis of the REBID data for the past three years may be summarized in Table I below. This data considers projects where successful power purchase agreements have been concluded and is representative of installed capacity in megawatts (MW).

TABLE I
CONSOLIDATED RENEWABLE PROJECT DATA (2012 -2014)

	Wind	**PV**	**Small projects**	**Small Hydro**
Maximum (MW)	140,0	75,0	5,0	6,2
Minimum (MW)	20,6	5,0	1,0	1,2
Average (MW)	90,0	45,7	4,7	2,8
Median (MW)	77,2	32,9	5,0	2,4

This is a consolidation of all REBID power purchase agreements for the period ranging from April 2011 to March 2014.

The median for wind projects is 77.2 MW. A project of this magnitude would always be introduced on the HV busbar, hence was not considered for this study, as the focus was on embedded generation projects on the MV busbar. There was only one hydroelectric and one biomass power purchase agreement for the period analysed. As both technologies would have utilized synchronous generation, only Biomass, being the larger of the two was considered in the case study below. The majority of small projects represented photovoltaic projects and they were therefore modelled as such.

III. Fault Current Mitigation Options

The option of network reconfiguration was not considered in this study, for example, the action of operating with the busbar as shown in Fig. 1 split. This would reduce the fault level and come at zero cost but it would result in a loss of network reliability, which is an undesirable and unwanted consequence.

Here we focus on four possible fault current mitigation solutions.

A. Air core reactor

The series connected air core reactor represents the traditional option for fault current management in a power network. It is a passive device that requires minimal maintenance, has a small physical footprint and is available at a cost that is significantly lower than any of the other options considered. It is however continuously connected and therefore consumes considerable electrical power. The associated volt drop is compensated for by on-load transformer tap changers that regulate the voltage on the MV busbar.

For this comparative study an 11 kV unit with a rated inductance of 3.05 mH per phase was selected as this unit complies with ESKOM's specification and is currently utilized on the network. Although the rating can be customized per substation, standardization is preferred to reduce costs and minimize strategic spares holding.

B. High impedance transformer

Standard transformers on the South African power grid are specified with an impedance that ranges between 8 – 10 %. High impedance transformers with an impedance range between 18 – 20% have recently been introduced by Eskom as a fault level management measure. This passive mitigation measure operates on the same electrical principle as an air core reactor and therefore shares many of its advantages and disadvantages. The one major advantage it has over an air core reactor is that it requires no additional space in an electrical yard and is therefore an ideal option when a retrofit solution is required.

When considered as a solution to lower the fault level due to the availability of localized generation on the MV busbar, the losses are not technically higher, as the energy loss is a function of the load current that passes through the transformer, and the load current is often reduced in these instances. Although often cited [8] as a costly option, these high impedance transformers are available via long term contracts at a premium that ranges between 5.6% and 6.4% of the price of a standard transformer for the various voltage options. It is therefore an ideal option for new installations where it is perceived that fault levels are, or will become, a concern. When utilizing this option however, power utility needs to also consider the additional costs associated with increased strategic spare holding.

C. Equipment uprating

As discussed above, high fault levels are not undesirable, as long as equipment is appropriately rated. Many of the substations identified where the fault level of the breaker has been exceeded have equipment installed that has passed or is nearing the end of its service life. Replacement of these breakers during refurbishment projects, with those that comply to the current breaker specification (fault level rating of 25kA) [9], would eliminate the need for any further fault level management intervention. This is however a costly and time consuming option. The choice of merely replacing the equipment in a substation yard when it is identified that the fault level has increased beyond the equipment rating is not always practical. For example, substation components like the substation earthmat, would have been designed for a particular fault level, and would have to be strengthened to ensure compliance viz. touch and step potentials. The equipment uprating option does however have no increased maintenance or operation (energy loss) cost

D. Superconducting Fault Current Limiter

Recent installations of resistive superconducting fault current limiters on power grids has propelled this technology from the laboratory into a potentially viable alternative for fault level management. It is the only active device to be considered for this study i.e. a device that only 'engages' when a fault is introduced to the power system. The device operates by allowing load current to transparently pass through superconductor tape/wire that have been cooled to below their critical temperature thereby presenting no resistance and therefore no loss to the network. When a fault is introduced, the current increases above a threshold value which causes the superconducting tape to change phase and introduce resistance into the system within the first half cycle thereby "instantaneously" reducing the fault current. It is assumed that the SFCL is installed on the 11 kV busbar in Figure 1, but if the SFCL replaces the existing bus-section breaker, then it would result in reduced operational flexibility. To overcome this, the SFCL should be installed in conjunction with a bus section breaker.

The energy required for this option is primarily for the cooling requirements and is therefore independent of load current. Operating costs were determined using calculated energy losses based on the 'Eccoflow' installation in Mallorca [1] which was a closed cycle cooling system. Although an open cycle cooling system would utilize significantly less electrical energy, it would require increased specialized maintenance and operation. The purchase price for a resistive SFCL was obtained from the recent procurement by Western Power Distribution (WPD) of two SFCL's to "future-proof" the Birmingham power distribution network [10]. This was the most recent cited example of a SFCL purchased to manage fault levels on a utility grid.

IV. Case Study

A case study was selected as the best way to evaluate the various fault level management options. The study would quantify parameters for the various options and could then be used when considering suitable fault level mitigation methods at other installations. A substation which is located in the province of KwaZulu-Natal in South Africa was selected, as the existing fault level was between 90 – 100 % of the equipment rating. This was done to verify the possible impact that localized generation could have at substations where breaker ratings have not been exceeded as yet and to also verify the effectiveness of the different fault level mitigation options.

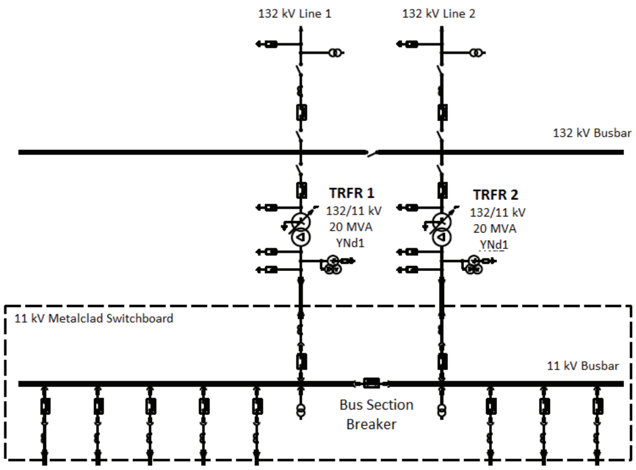
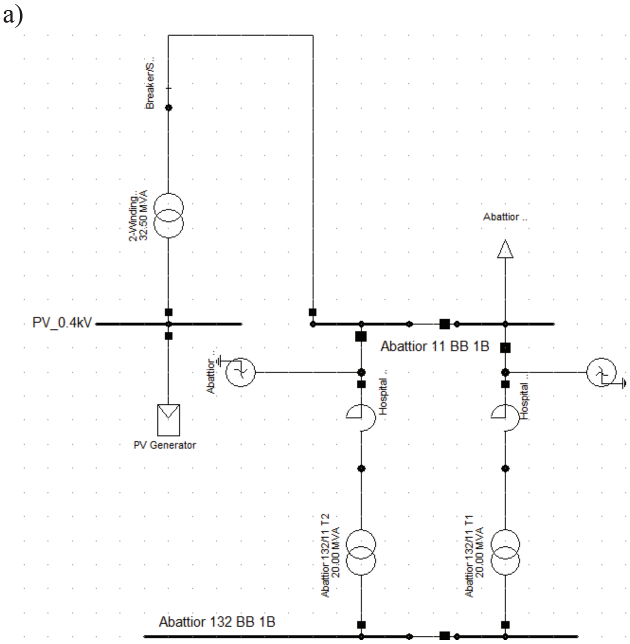


Fig.1. Operating Diagram of the selected substation

A. Fault Level Simulations

Simulation and analysis software, DIgSILENT PowerFactory™ was used to model this substation and the impact that various renewable energy projects could have on its existing busbar fault level rating. This was achieved by simulating the median capacity for the various technologies identified in Table I and observing the impact that it could potentially have on the existing fault level at the substation busbar. The breakers presently installed at the substation chosen for the case study has a fault level rating of 18.4 kA.

a)



b)

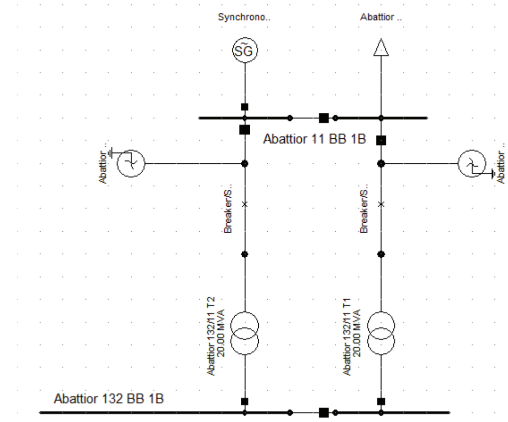


Fig.2. DIgSILENT™ models for a (a) Photovoltaic Project and (b) Synchronous generator (hydroelectric and biomass projects)

Table II shows one the impact on simulated short circuit fault level when various renewable technologies are introduced to the local system. It also shows the effect on breaker rating exceedance as a percentage of the breaker rating and confirms the effectiveness of both the specified series reactor and high impedance transformer as an effective fault level management device.

An analysis of Table II indicates that with the exception of the 5 MW photovoltaic in-feed, all other simulations indicate that the breaker rating would be exceeded for the various renewable technologies considered and an intervention would therefore be required to ensure operational safety.

TABLE II

IMPACT OF RENEWABLE ENERGY PROJECTS AND MITIGATION OPTIONS ON BUSBAR FAULT LEVEL

		3 phase I_{SC}	**Breaker Exceedance**
Existing		17.843kA	96,97%
5 MW Hydro Generator	Impact on Fault level	19.413kA	105,51%
	Series Reactor	9.36kA	50,87%
	High Impedance Tx	11.41kA	62,01%
16 MW Biomass Generator	Impact on Fault level	24.1kA	130,98%
	Series Reactor	13.98kA	75,98%
	High Impedance Tx	16.05kA	87,23%
5 MW Photo-voltaic Plant	Impact on Fault level	18.13kA	98,53%
	Series Reactor	8.1kA	44,02%
	High Impedance Tx	10.1kA	54,89%
30 MW Photo-voltaic Plant	Impact on Fault level	19.64kA	106,74%
	Series Reactor	9.741kA	52,94%
	High Impedance Tx	11.79kA	64,08%

B. Energy Loss Calculations

The primary difference between a passive and active fault current mitigation measure is that the passive measure is not transparent to the grid and 'always – on', for example the series air core reactor and therefore traditionally more energy intensive whereas the active measure has minimal losses (effectively transparent to the grid) and limits current only during fault conditions [11]. The energy loss and cost associated with different fault current mitigation methods needs to also be considered in order to help make informed decisions.

The energy loss associated with the use of different fault current mitigation technologies has been simulated using DigSilent™ with the exception of the "equipment upgrade" option as this would result in a zero energy loss. A typical daily load profile was modelled at the selected substation to determine the increase in energy loss when utilizing either an air core series reactor or a high impedance transformer for a day. This was then used to determine the annual operational cost. Table III shows the daily energy usage for the various fault management technologies identified. The energy loss associated with the SFCL represents the energy required for the cryo-cooler. It was obtained by referencing the normal load current at the selected substation to the power loss associated with the design of an installed SFCL [1]. This increased energy loss would then be monetarily quantified to ascertain the operating cost of the varying options.

TABLE III

DAILY ENERGY REQUIREMNTS ASSOCIATED WITH THE FAULT CURRENT MITIGATION METHODS IDENTIFIED

	Energy increase (kWh)
High Impedance Transformer	633,69
Air core series reactor	321,28
Equipment uprate	0
Superconducting fault current limiter	204

V. ANALYSIS OF FAULT LEVEL MANAGEMENT OPTIONS

A critical aspect that a power utility has to consider is the financial impact for choosing a fault level mitigation solution. In doing so, it is prudent to not merely consider the initial capital cost but to rather evaluate the lifecycle cost which includes costs associated with purchase, operation and maintenance [12]. At Eskom, primary plant equipment at substations are designed to have a service life of 25 years.

Capital cost data was obtained from recent purchase invoices or contracted purchase agreements with Eskom with the exception of the purchase price for the SFCL, which was the acquisition price for an SFCL recently purchased by Western Power Distribution [10]

Maintenance costs were only a factor for an SFCL and it was assumed that maintenance would be undertaken on the cryo-cooler once a year. However, in the South African context this cost would be an assumption and it was therefore excluded from the case study with the understanding that the reader is aware that an additional undetermined maintenance cost is applicable to the SFCL whereas all other technologies evaluated would have a zero or negligible increase in maintenance costs. The energy cost was determined by using existing energy prices with a constant inflation of 6% to more accurately determine the lifecycle cost over 25 years.

TABLE IV HERE

Although the air core reactor has the lowest capital investment cost, it has a considerable energy cost with the high impedance transformer having the highest energy cost. Of all the options evaluated, the series reactor was found to be the most cost effective over a 25 year time period. The equipment uprate option was in this example the next best option. One of the primary reasons for this is that the breakers concerned where of the indoor metal-clad variant and that significantly reduced the constructability costs. As mentioned earlier, this study assumed that the earth-mat in the substation yard does not require uprating. The installed circuit breakers at the selected substation were installed in 1978 and have therefore surpassed its service life of 25 years. It therefore has a zero net asset value. Refurbishment of this substation would result in the circuit breakers being replaced, and the new circuit breakers on contract with Eskom are rated for a fault level of 25 kA. For this case study therefore it is clear that the solution to the problem of breaker exceedance would be best addressed by uprating the circuit breakers even though it is not the most cost effective from a life cycle costing perspective.

The cost of utilizing a high impedance transformer as a solution to this example was found to be the most energy intensive option. When considering the high capital cost of the high impedance transformer, one must bear in mind that this solution combines a fault level management tool with an essential item of plant in the substation and that the true financial cost of this fault level exceedance solution is therefore the total cost of the project less the remaining asset value of the existing transformers. As these transformers were purchased and installed in 1998, the present net book value on each transformer, due to the lower purchase price and the effect of accumulated depreciation is \$ 92, 105 each. The true financial cost of this option purely as a means to reduce the existing fault level is therefore \$ 1, 310, 434. One should however also bear in mind that utilisation of this option needs to be part of a much larger fault management philosophy as high impedance transformers would now be required to be purchased as part of the strategic spare fleet. Large-scale adoption of this philosophy could prove to be very expensive in the long term when factoring in the high energy cost of this option.

The very high initial capital investment cost for SFCL's remains the most significant factor in the high life-cycle cost determined for this option. It is understood that up to 3 km of (HTS) tape is utilized in the construction of a SFCL [1]. The cost of the HTS tape is known to be a significant factor in the overall capital cost of the SFCL and prices for this are decreasing and will decrease even further with improved market penetration. The operating energy cost of the cryo-cooler was found to be comparable with that of the air core reactor however, it is clear to see that even significant reductions in cryo-cooler efficiencies will not affect the life cycle costs substantially. For SFCLs to be viable for power utilities consideration in fault level management, extensive research and development on ways of reducing the initial capital cost is still required.

VI. Conclusion

This paper clearly shows that even small generation projects have the potential to result in breaker exceedance at a substation that needs to be addressed for operational and safety concerns. Of the fault level management technologies investigated for this case study, it was shown that the lowest 'energy cost' solution was not necessarily the most cost effective over a 25 year life cycle. There are many criteria to be considered when selecting an appropriate fault level management solution and these are, but are not limited to;

- Space Constraints
- Age of equipment, and
- Carbon emission reduction

An important note to consider is that this case study was done from an Eskom point of view and that Eskom is one of the top 10 utilities in the world by generation capacity. It generates approximately 45% of all the electricity used in Africa and has over 400, 000 km of lines and cables across all voltages. This allows, Eskom as a power utility to acquire very competitive prices for equipment. Hence, all cost used other than the cost of a SFCL was well negotiated. Another important consideration is that the cost of electricity in South Africa is also known to be very low. It ranges between \$26.89/MWh during off peak times in summer to a maximum of \$215.10/MWh during peak time in winter. Therefore, a vital outcome of this case study is that SFCLs need to reduce their capital cost to become a viable fault level management option in South Africa. This may not be the case for smaller utilities and countries where the cost of electricity is higher or higher penalties imposed for increased carbon emissions.

It would not be feasible for a power utility to adopt a single strategy to address the challenges of increasing fault levels. One should rather evaluate the various options for individual substations on a case by case basis as there are factors other than just cost that one needs to considered before deciding on a solution. As an example, a substation that is physical constrained may need to employ a high impedance transformer to lower fault levels. Furthermore, utilization of a superconducting fault current limiter may address other power system related concerns e.g. the reduction of transformer inrush current [13] or a network voltage unbalance improvement [14]. The components of SFCLs are evolving which will make them a more competitive option as fault level management solutions, for example, more efficient cryo-coolers and the reduction of the cost of HTS tape.

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TABLE IV
LIFECYCLE COSTS FOR FAULT LEVEL MANAGEMENT TECHNOLOGIES INVESTIGATED

	Series Reactor	Equipment uprate	High Impedance Tx	SFCL
Capital Cost	$ 160 238,58	$ 650 822,26	$ 1 494 644,62	$ 1 742 735,85
Energy Cost/ day	$ 15,09	0	$ 29,77	$ 9,58
Energy Cost (p.a)	$ 5 508,81	0	$ 10 865,46	$ 3 497,83
Energy Cost (25 years)	$ 302 238,12	0	$ 56 238,52	$ 18 104,41
Total lifecycle Cost	**$ 462 476,70**	**$ 650 822,26**	**$ 1 550 883,14**	**$ 1 760 840,26**

assumed an exchange rate of R 14.21/ 1 Euro and R10.60/ $1

assumed a long term inflation rate of 6% pa for energy prices