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An approach for economic evaluation of superconducting fault current limiters in city grids with relay protection considerations

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SUMMARY

The paper updates the technical and economic calculations of superconducting fault current limiter application proposal in the Moscow power system taking into account the contemporary cost and technical parameters of equipment (switchgear and SFCL). It is shown that despite using a larger number of SFCL to eliminate grid splitting, SFCL implementation is preferable in comparison with the traditional methods such as switchgear replacement.

KEYWORDS

Superconductor – Fault Current – Short-Circuit Current – Fault Current Limiter – Grid Splitting.

INTRODUCTION

Mass production and commercial availability of second generation high-temperature superconductor (HTS) [1] enabled creation of a new type of electrical equipment - Superconducting Fault Current Limiter (SFCL) [2].

SFCLs are designed as solution for power grids for [3]:

1. short circuit current reduction,
2. enabling independence of power supply,
3. improving power generator stability.

Short-circuit current management in power systems has several traditional solutions, namely: grid splitting, installation of current-limiting reactors (CLRs) and replacement of electric switchgear with new ones with increased breaking capacity [4]. Each of these solutions have its shortcomings:

1. Grid splitting reduces power supply redundancy since it reduces the number of supply centers and it is considered only a temporary measure.
2. Installation of CLRs in a number of cases (specifically in the Moscow grid) has technical limitations: mass installation of CLRs with high impedance (several tens of Ohms) reduces short-circuit current but leads to a significant voltage drop between substations which results basically in grid splitting, especially in emergency regimes with characterized with high load currents. Installing a lower impedance CLR reduces fault current temporarily and, consequently, requires return to grid splitting to manage increasing faults [5, 6].
3. Replacement of switchgear with increased breaking capacity usually requires a large amount of monetary and administrative resources as it involves the replacement of a large number of electrical equipment up to the complete substation reequipment.

Installation of SFCLs is considered as a novel approach to short-circuit current management. It is clear, that only two approaches should be considered as long-term measures: a) traditional - replacement of electric switchgear with new and b) alternative - installation of SFCLs. Option a) provides the grid with increased breaking capacity equipment capable of withstanding increasing levels of short-circuit currents while option b) ensures that short-circuit currents in the adjacent network are reduced to values that can be disconnected by the existing switchgear.

At the qualitative level, these options had been compared [3]: SFCL application in power systems of large cities, in particular, Moscow, should be considered as an alternative to large-scale replacement of circuit breakers. At the same time, the quantitative assessment of SFCL application effect in comparison with traditional solutions is presented to a limited extent in public media.

For the power system of Moscow and Moscow region in 2016, an analysis of the economic effect of SFCL application to reduce short-circuit currents was performed [5]. This work was carried out using the relay protection and automation system software which allows short-circuit current calculations of electric grids using the method of symmetrical components. Grid models were in accordance to [7, 8] and calculation results were verified by the System Operator (JSC “SO UPS”).

To quantify the SFCL application effect two scenarios were proposed with their cost quantified: a) traditional - replacement of electric switchgear and b) alternative - SFCL application.

For the traditional scenario, the following algorithm was used to determine costs:

1. The network topology was changed by connecting the 220 kV transit lines of the center of Moscow (which were split due to excessive short-circuit currents), with short-circuit currents under such topology were calculated.
2. It was determined on how many feeders (switches) short-circuit currents exceeded the tripping capacity.

3. The cost of replacing switches with devices with sufficient tripping capacity was determined.

It was shown that 260 switches had to be replaced in this scenario, with $1,171 million capital costs at the dollar exchange rate at the time the paper was published [5].

The following algorithm was used for the alternative scenario:

1. The topology of the network was changed by installing 10 pcs. SFCL, 40 Ohm resistance, in 220 kV transit lines of the center of Moscow city which were disconnected due to excessive values of short circuit currents.
2. It was determined on how many feeders (switches) despite SFCL installation still required switchgear replacement (due to excess of tripping capacity, excess of the service life or other reasons).
3. The cost of replacing switches with devices with sufficient tripping capacity along with SFCL installation was determined.

It was shown that the alternative scenario required replacement of 14 switches to the sum of $76 million along with installation of 10 SFCL to the sum of $260 million. Combined, the estimated cost of the alternative scenario was $336 million at the time the paper was published, which is much less than the cost of traditional scenario.

However, the abovementioned work [5] was made with several assumptions:

1. SFCL resistance was taken as fixed value (40 Ohm, active resistance), since the relay protection and automation system calculation software used performs calculation via symmetrical components method which assumes fixed impedance values.
2. The SFCL cost was assumed based on the only available similar project - 220 kV SFCL at 220/20 kV Mnevniki substation in Moscow [3].

Taking into account the recently accumulated data on technical and cost characteristics of SFCLs, it is reasonable to update credibility of assumptions listed which is a goal of this paper.

APPROACH

1. Assumption on SFCL resistance

It is known that the SFCL has a nonlinear resistance characteristic which depends on a) duration and b) predicted short-circuit current (i.e. the estimated current value through the line assuming zero resistance of the SFCL) [2,9]. These dependencies are given on the manufacturer's website [10] in the document on technical characteristics of SFCL (shown in this paper as well - Fig. 1, 2). SFCL 6.6 Ohm was selected by the manufacturer in order to simplify onsite relay protection setup provided high SFCL resistance may hinder relay protection setup [11].

To satisfy assumption on SFCL resistance in [5], the SFCL shall develop 40 Ohm resistance in a time shorter than switchgear breaking operation which as a rule does not exceed 50 milliseconds (in the estimation of article's authors). At the same time, the load (predicted current) through the SFCL is 40 kA at minimum (the lowest value of the tripping capacity of switches replaced in the work [5]). The data on SFCL resistance for 220 kV voltage class depending on time and current (calculated current values are given assuming zero resistance of the SFCL) are available on the manufacturer's website (duplicated in the article, Fig. 2).

It can be seen that at the predicted current value of 40 kA, SFCL resistance does not depend on the current and it is 6.6 Ohm at 50 ms which is 6 times less than the value used in this work (40 Ohm). Thus, assumption of the SFCL resistance of the paper [5] is feasible under the assumption of installation of 60 SFCLs with characteristics according to [10] (each 40 Ohm SFCLs is replaced by 6 SFCLs with 6.6 Ohm resistance), which should impact the cost of alternative scenario (SFCL installation) described in the next section.

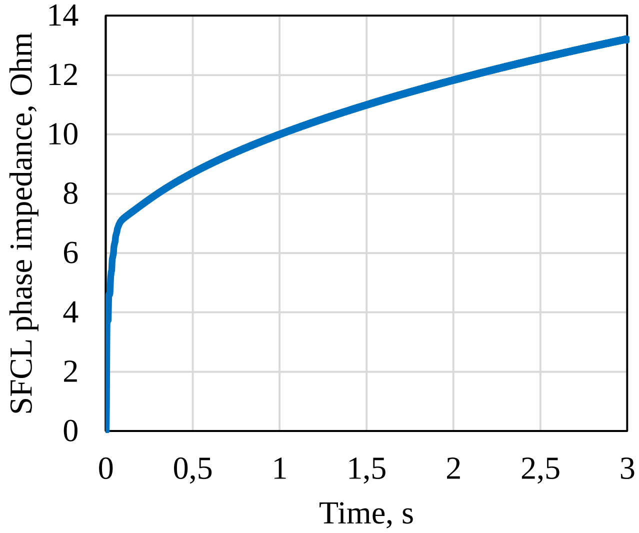

Figure 1 – Resistance dependence of 220 kV SFCL on short-circuit duration at expected short-circuit currents over 15 kA [10].

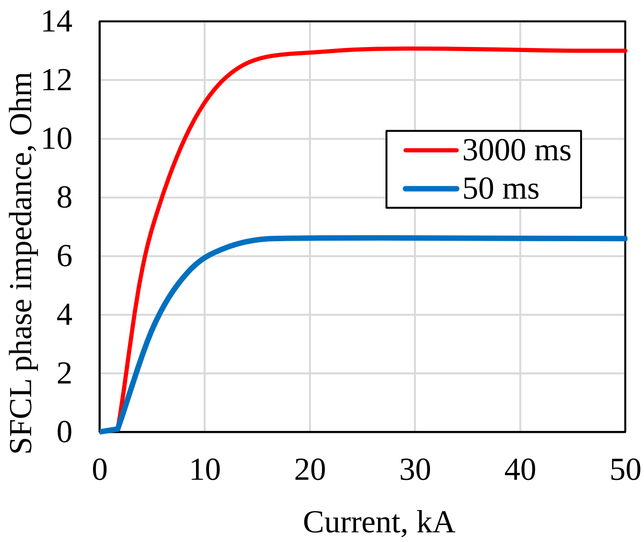

Figure 2 – Resistance dependence of 220 kV SFCL on expected short-circuit current value (assuming zero resistance of SFCL) [10].

2. Assumption on SFCL cost

The pilot 40 Ohm SFCL which cost was used in the paper [5], is a unique sample built taking into account the specifics of a particular installation site - 220/20 kV Mnevniki substation. Since SFCL deployment at different locations in the power system is assumed in the paper [5] the application of unique pilot solutions may be limited.

In particular, the thermal resistance of 40 Ohm SFCL at the 220/20 kV Mnevniki substation is 400 ms [3]. At the same time, standards for typical current-limiting equipment [12, 13] require much higher thermal resistance in range of 2 - 3 seconds.

Such thermal resistance has 6.6 Ohm SFCL [10]. According to the manufacturer's statement, the cost of device such is 22 million dollars.

Thus, for correct comparison of traditional (switchgear replacement) and alternative (application of SFCL) scenarios it is reasonable to use technical and economic parameters of the 6.6 Ohm SFCL (Table I), comparing installation of 60 pcs 6.6 Ohm SFCLs with replacement of 260 switches.

Table I – Technical and economic parameters of 6,6 Ohm SFCL.

Characteristic	Value
Rated voltage	220 kV
Rated current	300, 600, 1200
Resistance	6.6 Ohm @ 50 ms
Thermal resistance	2-3 s
Cost	$22 million

Since the paper [5] was prepared in 2016, it is reasonable to update the cost of switches by indexing their cost in accordance with inflation in the period of 2016-2023 according to the International Monetary Fund for the G7 countries - 24.4% [14], for Russia - 57.7% [15].

The costs of scenarios were calculated using the formulas:

1. Traditional

$$CAPEX\ 2023 = CAPEX\ SG\ 2016 * (1 + \frac{Inflation}{100}), \tag{1}$$

2. Alternative

$$CAPEX\ 2023 = CAPEX\ SG\ 2016 * \left(1 + \frac{Inflation}{100}\right) + N * SFCL\ cost, \tag{2}$$

where $CAPEX\ 2023$ – costs per the scenario in prices of 2023;
$CAPEX\ SG\ 2016$ – costs for switch replacement per scenarios in prices of 2016;
$Inflation$ – inflation in the 2016-2023 period according to data of the International Monetary Fund [13,14];
N – quantity of installed 6.6 Ohm SFCL;
$SFCL\ cost$ – costs of installation of 6.6 Ohm SFCL.

RESULTS AND DISCUSSION

As a result of calculations using formulas (1) and (2), the costs for two scenarios were determined: traditional (replacement of switchgear) and alternative (installation of SFCL) considering indexation of costs for switch replacement. The results are given in Table II. Costs for the alternative scenario (installation of SFCL) are lower than those for the traditional scenario) in range of $39-409 million, depending on the inflation percentage assumed. The magnitude of the effect can be even higher taking into account the possible cost reduction of the SFCL in high-volume production. Thus, SFCL application in the power system of Moscow is feasible and economically efficient.

Table II – Summary table of calculations by scenarios considering inflation [13, 14].

Costs indexation with adjustment for inflation	**Scenario 1 Traditional (260 pcs. of switches)**	**Scenario 2 Alternative (14 pcs. of switches, 60 pcs. of 6.6 Ohm SFCL)**	**Positive economic effect of SFCL application**
G7 countries - 24.4%	$ 1 452 million	$ 1 413 million	$ 39 million
Russia - 57.7%	$ 1 847 million	$ 1 438 million	$ 409 million

The approach based on the comparison of scenarios of switchgear replacement and SFCL installation can be used also for other electric grids to determine whether SFCL installation is effective or not. The popular short-circuit calculations via symmetrical components method may be used to estimate the effect of SFCL installation. This effect should be verified during subsequent engineering and construction, considering recent switchgear upgrades, onsite requirements and network reliability studies.

CONCLUSION

The paper updates the technical and economic calculations of SFCL application proposal in the Moscow power system taking into account the contemporary cost and technical parameters of equipment (switchgear and SFCL). It is shown that despite using a larger number of SFCL to eliminate grid splitting, SFCL implementation is preferable in comparison with the traditional methods such as switchgear replacement.

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