Impact of Circuit-breaker Maintenance on Life-cycle Cost Comparison for Fixed and Magnetically Controlled Reactors

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***Abstract*—Under light loading conditions, reactors provide an option for keeping voltages below steady state limits. In this paper, the impact of the number of operations of a circuit breaker on the choice of reactor technology (i.e. fixed versus magnetically controlled) is studied. In particular, the impact of circuit-breaker maintenance cost on the life-cycle cost of a reactor installation is evaluated. The study shows that when the expected number of circuit-breaker operations is high, it is beneficial to consider the use of a magnetically controlled reactor as this leads to very few operations. In addition, the savings in circuit-breaker maintenance cost can justify the extra cost of a magnetically controlled reactor over its life cycle. The economic life-cycle cost assessment can help to identify the lowest cost solution over the project life cycle.**

***Index Terms*—Cumulative present value, maintenance of circuit breakers, depreciation, fixed-shunt reactor, life-cycle cost, magnetically-controlled shunt reactor.**

I. INTRODUCTION

In order to meet the quality of supply requirements [1], power systems are designed and operated so that steady voltages are kept within a defined, acceptable band [2].

When voltages are expected to be outside these limits, reactive power compensation is often a solution that is first considered to resolve the problems. In some cases, the load power can change to low levels, and this can result in steady state overvoltages. To deal with this, a solution is to install a rector to compensate for excessive, capacitive reactive power that may be generated by a power system, leading to high voltages.

These reactors may be of a fixed type [3], i.e. fixed-shunt reactors (FSR), which are either in an on or off state without the possibility of using only a fraction of its rated reactance and can be inserted to compensate for capacitive reactive power in the system. During peak loading conditions these reactors may have to be removed in order to keep steady voltages from dropping below acceptable limits. This insertion and removal of the reactors requires that the circuit breaker, via which the reactor is connected to the network, is operated, i.e. switched in or out of the network.

Magnetically controlled shunt reactors (MCSR) operate differently. They are designed [4] to automatically change their inductance only to levels that meet system reactive power compensation requirements. They are able to vary their reactance from 3% to full rating in about 0.7 s, a relatively fast response time. They are fully automated, needing no intervention by operators. Thus, the circuit breaker through which the MCSR is connected to the system does not have to be operated to adjust reactance. Its main purpose becomes the disconnection of the reactor from the system as is a requirement for maintenance.

The number of times the load varies between peak and off-peak levels will have a great influence on the number of operations a circuit breaker of fixed reactor will be subjected to over its life. This number has a direct impact on the maintenance of the circuit breaker and cost thereof over its life cycle. This affects the total life-cycle cost of the reactor installation.

In order for the utility to continue delivering power to its customers at a reasonable, the utility must not only ensure that there is enough and prudent capital investment in infrastructure. It must also ensure that assets in service [5] are maintained to increase their availability and to ensure that the expected life of assets is realized. Maintenance must be done to meet these objectives. For these reasons, the circuit breakers applied to switch shunt reactors also have to be maintained.

In this paper, the authors present the results of a study of the impact of the maintenance cost of shunt-reactor circuit breakers on the choice of the shunt-reactor technology (i.e., between FSR and MCSR) for a technology to be used to limit steady overvoltages. Life-cycle cost analysis, entailing the evaluation of cash flow items for the options, is used in the study.

The paper is divided into the following sections. In Section II, a brief description of the principle of MCSR operations is presented. The considerations evaluated in deciding on maintenance regimes of circuit breakers are discussed in Section III. Various cashflow items in fixed- shunt reactor and MCSR projects are discussed in Section IV. In Section V, the details of the case study undertaken and the assumptions made are presented. The results of the case study are then outlined in Section VI, with the conclusions presented in Section VII.

II. Principle of Operation of Magnetically Controlled and Fixed-Shunt reactors

The magnetic system of each phase of an MCSR consists of a high voltage winding and a control winding, as illustrated in Figure 1. When a regulated DC voltage is applied to the control winding, the current $i\ *_c$ flows in the winding and induces a flux in the core [6]. This flux is superimposed on that in the high voltage winding, driving the core into saturation. By regulating the current in the core, the degree of saturation and thus, the amount of capacitive reactive power that can be absorbed by the reactor, can be regulated.

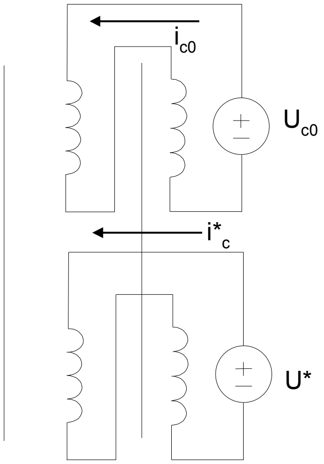

Figure 1: Components of a magnetically controlled shunt reactor [7].

The layout of the key components of the MCSR and how they interface, with the power system is shown in Figure 2. During the low loading condition, there is excessive reactive power generation in the network and this can result in high voltages at the nodes of the system.

This is detected [8] by the voltage transformer (VT) and the automated control system (ACS) and orders the increase of current flowing in the control winding of the MCSR. This increases the saturation of the MCSR and leads to increased consumption of the reactive power. In the case of high loading, the reverse of the process described is applicable.

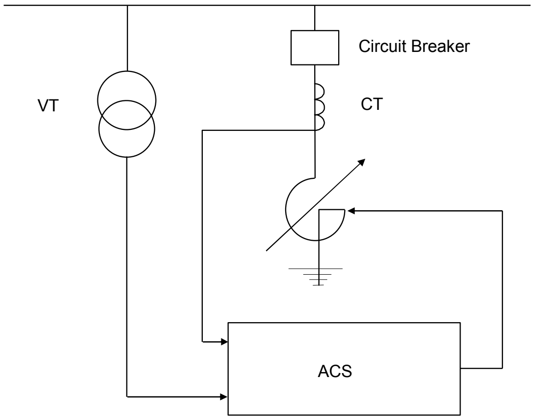

Figure 2: Components of a magnetically controlled shunt reactor (adapted from [8]): VT-voltage transformer, CT-current transformer, ACS: automated control system.

III. Standard Requirements for Maintenance of Circuit breakers

According to IEC/SANS Standard [9, 10], circuit breakers are mechanical switching devices which are designed to open or close one or more electric circuits by means of the separable contacts [11]. They are designed and type tested [12] capable of a certain number of closing/opening operations if the maintenance programme prescribed by the manufacturer is followed. For this purpose, circuit breakers are classified into two groups according to their mechanical endurance: (I) class M1: these are circuit breakers designed for standard mechanical endurance and should be able to do 2,000 operations and (II) class M2: designed for special service requirements and have an extended mechanical endurance. They should be able to do 10,000 operations.

For the M1 class circuit breakers, which will be considered in this paper, a typical maintenance regime could consist of minor maintenance after 500 and 1,500 operations. After 1,000 operations, major maintenance may be specified, and, after 2,000 operations a decision may be made to either replace the circuit breaker or to perform major life-extension refurbishment on it.

The maintenance intervention at correctly established intervals by the original equipment manufacturer (OEM) and experience of the utility helps to prevent excessive wear which affects the successful arc-quenching capability. It is important to perform maintenance that is adapted to the number of operations of the circuit breaker when it used to switch shunt reactors, to prevent the premature wear from developing further to the detriment of the successful switching of the circuit breaker.

IV. Cash Flows for Reactor Installations

Two options will be discussed here, namely, (I) installing an FSR and its circuit breaker and (II) installing an MCSR and its circuit breaker. The various cash flow streams applicable are briefly described below.

A. Cost of Equipment

This comprises the capital cost of purchasing the respective reactor types and the cost of purchasing the associated breakers required.

B. Maintenance Costs of Equipment

To maintain the equipment in good condition, a maintenance regime has to be put in place. The cost of this maintenance escalates annually by the consumer price index, $rcpi_n$, and can be calculated by equation (1)

$$O\,\&\,M_n = O\,\&\,M_o * (1 + rcpi_n)^n \tag{1}$$

where $O\&M_0$ is the initial cost of maintenance and $O\&M_n$ is cost of maintenance in year n.

C. Tax Allowance on Maintenance

A portion of the maintenance costs is subtracted from the income before actual tax payable is calculated. The expression that is used is equation (2)

$$O\,\&M_n Allowance = O\,\&\,M_o * (1 + rcpi_n)^n * TaxRate \tag{2}$$

where TaxRate is the tax rate applicable to corporate entities.

D. Tax Allowance for Depreciation

Tax allowance is also made for capital acquisition on the wear and tear of equipment due to usage. Equation (3) is used to calculate tax allowance for depreciation

$$Depr.Allow. = Capital * Depr.Rate * TaxRate \tag{3}$$

where *Depr.Rate* is the portion of capital assumed to have depreciated and *TaxRate* is the tax rate applicable to corporate entities.

E. Present Values of Cash Flow Items

To bring all future cash flows to the present, the equation (4) is used to determine the present value of each annual cash flow item.

$$PV = \frac{NetCashFlow_n}{(1 + r_{ndr})^n} \tag{4}$$

V. CASE STUDY: COMPARISON OF LIFE-CYCLE COST FOR FSR AND MCSR FOR SUPPLY TO HIGHLY VARYIABLE LOADS

A. Description of Network Problem and Solutions

The geographical layout of the Kimberley network, which is used in the case study, is shown in Figure 3. The topology of the network is characterized by lines that generate significant amounts of capacitive reactive power. The transmission stations are far from some loads, meaning there is limited control of voltage that can be provided by these transformers.

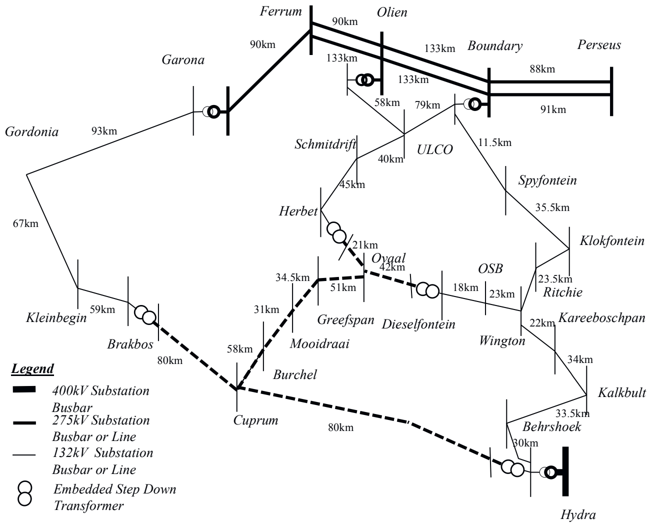

Figure 3: Geographic layout of the Kimberley distribution network, showing the lengths of 132 kV lines.

The loads supplied by this network are moving, i.e. once ore is mined in one area, lines are extended to a new area to be mined. There is also an agricultural load component in the area on a special tariff that encourages pumping at one particular time (afternoon), which leads to load increasing at this time and a significant drop at night. The voltages can be outside the acceptable range of 0.95-1.05 per unit kV stipulated by the planning standard.

Recent network expansion studies recommended the following solution to alleviate the experienced voltage constraints:

- Solve low voltage problems during peak: Commission 4 x capacitor banks at Ovaal substations. The estimated total cost was R 12 million. The date of commissioning was July 2016. R=ZAR=South Africa Rand
- Solve high voltage problems during off-peak: Commission a 10 MVar, 132 kV fixed-shunt reactor Ovaal substation. The estimated cost was R5.5 million for the reactor and R800 000 for the reactor circuit-breaker. The date of commissioning was July 2016.

  The possibility of using MCSR was identified as a possible alternative to using fixed-shunt reactors to solve high voltage loads during low loading conditions. The cost of a 10 MVar, 132 kV MCSR was estimated to be R7.2 million by the supplier. This would require the same circuit breaker as the fixed-shunt reactor (cost of R800 000). The assumptions in the life-cycle cost comparison are summarized in the next section.

B. Major Assumptions in the Economic Comparison

The major assumptions in the case study in evaluating the life-cycle costs of the fixed reactor and MCSR are as follows.

- The life-cycle evaluation is done over a period of 25 years.

- The cost of a 132kV, 10 MVar fixed-shunt reactor, is R5.5 million.
- The maintenance cycle of its circuit breaker is as follows: minor maintenance at 500 and 1,500 operations at 10% of capital costs, significant maintenance at 1,000 operations at 40% of capital cost, and end of life at 2,000 operations and major refurbishment at 60% of capital cost (assumed) or replacement.
- The fixed-shunt reactor circuit breaker is assumed to operate once a day. This means 365 operations per annum. For the circuit breaker designed for 2,000 operations, maintenance will be required in 1.4 years (~2 years), 2.7 years (~3 years), 4.1 years (~4 years) and a major overhaul in year 5.5 years (~6 years). This cycle is repeated with the 2nd, 3rd, and 4th breakers
- The cost of an MCSR is R7.2 million, excluding the circuit breaker.
- The MCSR's circuit breaker is maintained once a year at a cost of 1.5% of the capital costs.
- The cost of a 132kV circuit breaker (designed for 2 000 operations) is R800 000.
- The tax allowance for depreciation calculated on capital costs is 40% in year 1, and 20% thereafter.
- The CPI is 5% and the nominal discount rate is 10.3%.
- The corporate tax rate is 30%.

VI. RESULTS AND DISCUSSIONS

In Figure 4 the cumulative present value (PV) of costs of both the MCSR and FSR is presented. The cash flow structures, i.e. expenditure (cost of maintenance) and income (tax allowance on maintenance and tax allowance on depreciation), are similar for both reactor types and only vary because of the difference in initial capital costs of the reactors. This is reflected in the similarity of the cumulative PV profiles.

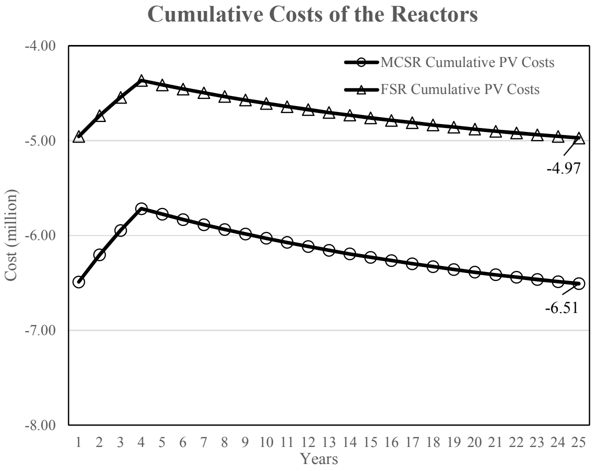

Figure 4: Cumulative present value of the MCSR and FSR costs.

The cumulative PV of circuit-breaker costs for the circuit breakers used in the two reactors is shown graphically in Figure 5. The cost profile for the MCSR circuit breaker is flat and stable over the life cycle. For the FSR circuit breaker there are significant changes in the costs since more expenditure is needed at intervals called for by the standards, including major overhauls and end of operational life cycle.

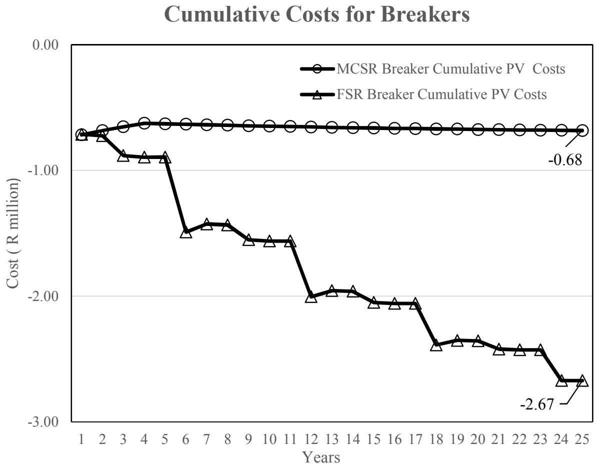

Figure 5: Cumulative present value of the cost of circuit breakers for the MCSR and FSR.

The total cumulative PV of installation costs (i.e., circuit breakers and reactors) for the two technology options is shown in Figure 6. In the initial phases, the costs of the FSR installation are less than those of the MCSR installation. As the years of service increase, there is a higher accumulation of costs for the FSR installation, and these costs equal and exceed those of the MCSR installation, around year 18 and thereafter.

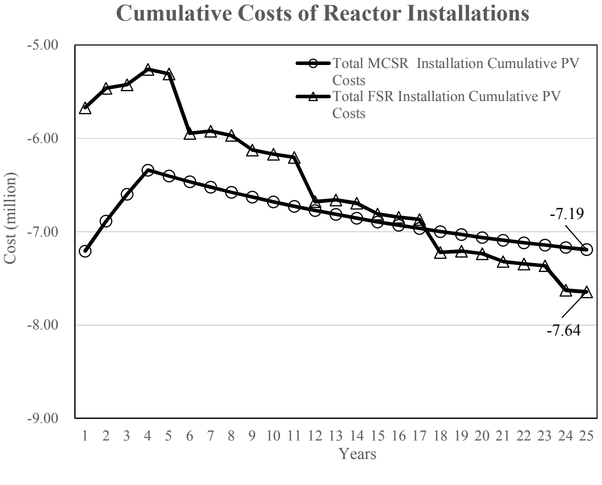

Figure 6: Cumulative present value of the total cost of the MCSR and FSR installations (i.e., reactor and circuit breaker).

The net PV of the life-cycle costs of both installations are shown in Figure 7. These costs are R7.64 million and R7.19 million for the FSR and MCSR installations, respectively.

Although the costs of the MCSR are higher initially and during the initial phases, at the end of the life cycle, the cumulative costs of ownership are lower.

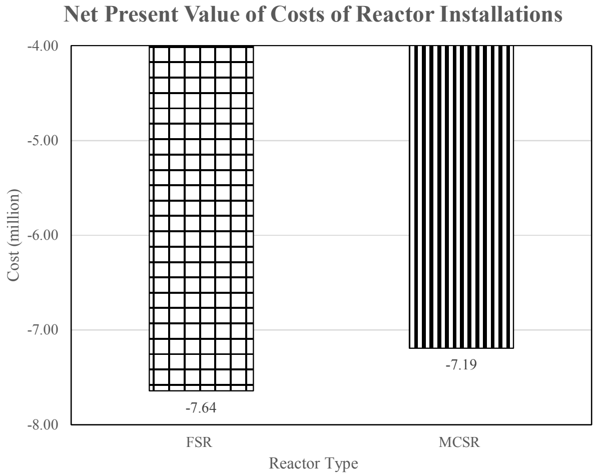

Figure 7: Net present value of costs of the installations for the MCSR and FSR installations.

VII. CONCLUSIONS

In this paper the impact of circuit-breaker maintenance costs in deciding between the use of MCSRs and FSRs is presented. The circuit breaker life-cycle costs are formulated as a function of the number of operations and these costs are combined with those of the reactor to obtain the total costs of the installations.

The initial costs of the FSR installations are lower as the capital costs dominate. As the installations continue to be in service, the accumulated operational costs of the FSR circuit breakers can rise more rapidly, and this rise can increase appreciably with a higher number of circuit-breaker operations. In contrast the operational costs of the MCSR installations remain flat.

The study has shown that maintenance costs of reactor breakers, a function of the number of circuit-breaker operations, can have a significant impact in the choice of reactor technology. Before finalizing the technology choice, the number of operations should be assessed and the framework presented in this paper can be used to determine which technology delivered a solution with lowest life-cycle costs.

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REFERENCES

[1] Electricity Supply-Quality of Supply, Part 2: Voltage Characteristics, 2nd Edition, NRS 048-2: 2003.

[2] *Transmission System Planning Standard*, Eskom Holdings SoC Limited, System Operation and Planning Division, Johannesburg, March 2009.

[3] P. Kundur. *Power System Stability and Control*. McGraw-Hill, Inc., New York: USA, 1993.

[4] A. M. Bryantsev, M. D. Galperin and G. A. Edvokunin, Magnetically Controlled Reactors Enhance Transmission Capability and Save Energy-Especially in Compact Increased-Surge Impedance Loading Power Lines, Available:http://www.cerc-reactors.com/articles/nsf-epri-011010.pdf (accessed 17 September 2015).

[5] L. Ndjenja and J. K. Visser, "Development of a Maintenance Strategy for Power Delivery Plants," Vol. 106, Issue 3, September 2015, pp. 132-140.

[6] Magnetically Controlled Shunt Reactors. [Online]: Available: http://exportreachout.com/E44C94E4-B5C5-4D07-B6B1-1ECFBE1ED210/FinalDownload/DownloadId-7CD9B1515E094019B65CD395C8C81DAC/E44C94E4-B5C5-4D07-B6B1-1ECFBE1ED210/wp-content/uploads/2012/09/MCSR-brochure-eng-1.pdf (accessed Juy 2015

[7] R. Bogdanovics, Magnetically Controlled Shunt Reactors Overview. [Online]. Available: http://egdk.ttu.ee/files/parnu2015/Parnu_2015_152-153.pdf (accessed 17 Sept 2015).

[8] A. Bryantsev, M. Bryantsev, B. Bazylev, S. Dyagileva, A. Negryshev, R. Karymov, E. Makletsova and S. Smolovik. Power Compensators Based on Magnetically Controlled Shunt Reactors in Electric Networks with a Voltage between 110 kV and 500 kV, Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), 2010 IEEE/PES.

[9] South African National Standard, High-voltage Switchgear and Controlgear: Part 100: Alternating-current Circuit Breakers, SANS 62271-100:2013 Edition 2.1 and IEC corr. 1 March 2013.

[10] SANS 60050(441):1984, International Electrotechnical Vocabulary (IEV) − Chapter 441: Switchgear, Controlgear and Fuses.

[11] M. Kapetanovic, "High Voltage Circuit Breakers", ETF – Faculty of Electrotechnical Engineering, Sarajevo, 2011.