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SELECTING SWITCHES FOR SWITCHING INDUCTIVE LOADS: TECHNICAL ASPECTS AND PRACTICAL CONSIDERATIONS

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Abstract*: In power systems, reactive compensation is a common and necessary practice to maintain the quality of electrical service. Disconnection of reactors or reactor banks is frequent, sometimes up to two or three times a day. Therefore, circuit breakers for this application must operate satisfactorily under the energization and de-energization processes of "inductive currents" that can cause the chopping interruption phenomenon, as well as in cases of magnetizing currents from unloaded transformers and load currents from induction motors. The proper selection of circuit breakers to operate inductive loads in medium-voltage systems is a critical aspect in the design and operation of electrical networks. Inductive loads, such as motors, transformers, and reactors, present unique challenges due to the voltage and current transients associated with their connection and disconnection. This article addresses the essential technical criteria for breaker selection, including interrupting capacity, surge resistance, and arc flash management. In addition, relevant international regulations are discussed, and case studies illustrating industry's best practices are presented. The aim is to provide comprehensive guidance for engineers and designers seeking to optimize the reliability and safety of their electrical systems.*

1. INTRODUCTION

Reactive compensation in electrical power systems is vital for maintaining service quality and operational efficiency. It is commonly implemented using reactors or reactor banks that are connected and disconnected via medium-voltage circuit breakers. These breakers must withstand the significant transient events that occur during such switching operations.

Therefore, the correct selection of these devices is paramount, with special attention to the arc extinguishing medium, to prevent premature failures that compromise system reliability.

Inductive loads, such as motors, transformers, and reactors, store energy in their magnetic fields. Upon disconnection, this stored energy is released, generating voltage and current transients that can cause severe overvoltages [1, 2]. These phenomena, including inrush currents and electric arc generation, can compromise equipment integrity and reduce its operational lifespan [3]. Understanding these characteristics is essential for selecting a circuit breaker capable of handling these demanding conditions without failure.

This article presents a case study from a 220 kV substation where a reactor connected to a 34.5 kV bus, fed by the tertiary winding of a 230/125/34.5 kV autotransformer, was protected by several circuit breakers that failed prematurely. The reactor's nameplate data is shown in Table 1.

Table 1 Reactor data

Guy	PTD-20000/35T
Strain	34.5 kV
Current	209 A
Frequency	60 Hz
Ability	11800 kVA

Source: Chapa data

Initially, an air circuit breaker (installed in 1974) was used for protection and switching. It suffered severe damage, destroying one pole before its expected end of life. It was replaced by an oil circuit breaker, which experienced similar contact damage and was also replaced prematurely.

On June 12, 2013, a 36 GI-E25 type SF6 switch was installed with the following nominal data:

- ✓ Vn = 36 kV
- ✓ In = 630 A
- ✓ Interrupting Capacity = 25 kA

By June 2016, only three years into 20 years expected lifespan and after only 1,802 of a rated 10,000 operations the contacts required replacement due to excessive resistance. This recurrent failure pattern prompted a detailed investigation into the root causes, involving a review of testing protocols, operational records, and relevant literature.

This led us to begin a review and testing process to determine the possible cause of the failures in the aforementioned switches, consulting bibliographies and specialists in the field.

1.1. Brief theory on interruption of inductive currents

In a high-voltage system, reactors are used to compensate for reactive currents in the system. These reactors are connected to the tertiary delta winding of the autotransformers, using medium-voltage switches, generally located in high-voltage substations. These reactors or reactor banks are sometimes operated up to two or three times a day, so the switches must operate satisfactorily. Proper switch selection is of great importance to minimize the probability of failure.

The switching of reactors involves the interruption of small inductive currents, which can lead to the current chopping phenomenon and multiple reignitions during the interruption process [4]. These events generate high-magnitude, high-frequency transient overvoltages, formally known as Transient Recovery Voltage (TRV).

Also evident in the connection and disconnection of magnetizing currents of transformers without load, load currents of induction motors and load currents of transformers that feed shunt reactors [4].

When an inductive load is disconnected, the current lags the voltage by approximately 90°. As the contacts separate, an arc is established. At the first current zero crossing, if the dielectric strength between the contacts cannot withstand the rising recovery voltage, the arc reignites. This process can repeat, with the recovery voltage increasing at each successive zero crossing until the arc is finally extinguished. At that moment, the energy stored in the circuit's inductance (*L*) resonates with its inherent capacitance (*C*), generating a high-frequency oscillatory transient. The natural frequency (f_n) of this oscillation is given by:

$$fn = 1/2\Pi\sqrt{\mathrm{LC}} \tag{1}$$

For these applications, SF6 circuit breakers are more limited in their ability to withstand sharp increases in the transient reset voltage (TRV), which is the effective value of the peak voltage of the first half-wave of the alternating current component that appears between the circuit breaker contacts after the current has been extinguished. It has a very significant influence on the circuit breaker's opening capacity and has a frequency of the order of thousands of Hertz, depending on the electrical parameters of the system in the operating zone. This voltage has two components: one at the system's nominal frequency and the other, superimposed, oscillating at the system's natural frequency than vacuum circuit breakers with similar nominal characteristics. Therefore, for applications where the use of vacuum circuit breakers is possible, selecting them is the best option.

Calculating the Transient Recovery Voltage (TRV) is a very cumbersome and illogical process. However, it is important to take into account the peak value of the Transient Recovery Voltage (TTR), which ranges approximately three times the phase-to-ground voltage, with a very rapid rate of rise (Rate of Rise) of kV/μs. This parameter is more capable of withstanding vacuum interrupters than SF6 interrupters, as they interrupt the current at its first zero crossing.

There are some solutions to reduce the growth rates of the Transient Reset Voltage TTR such as the installation of capacitors, these prevent the switch from being overstressed specifically during the thermal recovery period that occurs during the first 2 µs after the current interruption, this solution has the disadvantage of cost and added complexity, in case of having to use large capacities the ferroresonance phenomenon may occur. Another solution is the opening and closing synchronized with the oscillations of currents and voltages or the use of a synchronizing relay that enables the switch to operate in a synchronized manner with the phase voltage of the system, *figure 1* shows the interruption of inductive currents in the plane.

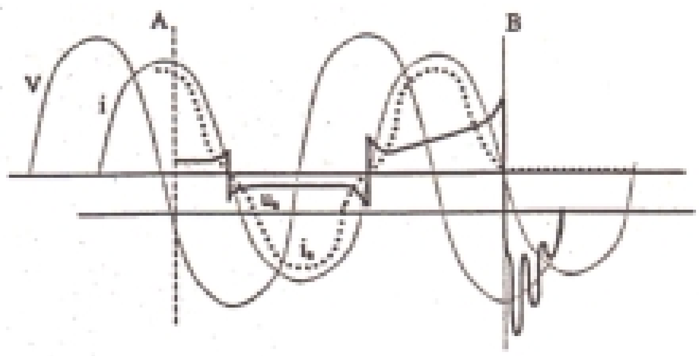

Fig. 1. Interruption of inductive currents.

2. METHODOLOGY

In this work the systemic method was used. To establish the relationship between the factors involved in the wear and tear or aging of the switches assigned to the connection and disconnection of inductive loads, through their testing protocols and the life records established by the company and by the statistical method for obtaining the behavior patterns of the state variables obtained from the documented records of their operation.

2.1. Review and testing process for the installed SF6 switch

During tests on the switch, a considerable deviation in contact resistance from the standard value of ≤ 100 µΩ for switches in service was observed. Measurements were taken during maintenance in 2016, and their values are shown in table 2.

Table 2: Results obtained in the tests carried out on the switch

Test I	Phase A	Phase B	Phase C
50 A	580 µΩ	82 µΩ	82 µΩ
100 A	468 µΩ	79 µΩ	82 µΩ
600 A	313 µΩ	81 µΩ	84 µΩ
100 A	232 µΩ	76 µΩ	91 µΩ

Source: [1]

According to the inquiries and bibliographical studies, the main causes of contact deterioration may be due to SF6 decomposition, such as oxidation and corrosion, contact wear, or pressure loss between contacts.

Several opening and closing operations were performed, seeking cleaning of the contacts and elimination of contamination if any, testing the contact resistance at 600 A where it can be used up to the nominal current, although deteriorated contact resistance values persist as shown in table 3.

Table 3: Contact resistance values after several opening and closing operations

Test I	Phase A	Phase B	Phase C
50 A	258 μΩ	70 μΩ	80 μΩ
100 A	269 μΩ	72 μΩ	74 μΩ
600 A	257 μΩ	72 μΩ	74 μΩ
100 A	266 μΩ	71 μΩ	74 μΩ

Source: [1]

The manufacturer's catalogue [2] establishes the contact resistance value in new switches as ≤50 μΩ, taking into consideration the latest values with 100A, we have that in phase A the contact resistance increases by 432% taking 50 μΩ as a base, in phase B it increases by 42% and in phase C by 48%, which shows serious problems in the contacts of the cutting chambers.

The manufacturer [2] proposes monitoring the wear of arc contacts and provides reference values:

- ✓ New arc contacts φ = 3.2°
- ✓ Arcing contacts with maximum permissible wear φ = 6.4°

To corroborate the above, the wear of the arc contacts is monitored, obtaining the following results table 4.

Table 4: Results of arc contact wear control

Switch phases	Poles of the failed switch (φ)
A	29°
B	27.5°
C	25°

Source: Chapa data

In the analysis of the contact resistance measurement results and in the arcing contacts wear control, the results show considerable wear on the main contacts and on the arcing contacts, the phase A the most damaged of the phases, which coincides with the phase that first opens, thus demonstrating the theory of the first pole to open.

Oscillographic tests were performed and all results were within standard, with no deterioration detected. The mechanical adjustment, i.e., the transmission regulation [5], was also reviewed, and it was verified that the value between points 1 and 2 coincides with the manufacturer's value of D = 2 mm, *fig. 2*.

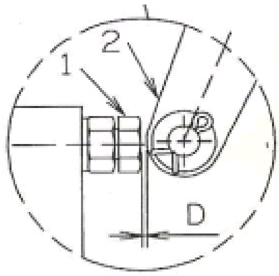

Fig. 2. Transmission regulation.

3. RESULTS

3.1. Analysis of measurement results

The diagnosis and monitoring of the condition of equipment and systems in real time comes from the 90s, particularly in the United States and Great Britain where the deregulation of the electricity market led to the search for new ways to reduce the costs of failures and increase reliability levels, in our case this monitoring and diagnosis is impossible and what is done is preventive maintenance that by procedure [6] is generally done once a year, bringing with it the detection of values that are sampled outside the parameter is late or in the worst case the failure surprises us.

The analysis of the contact resistance measurement results and the arcing contact wear monitoring in the SF6 circuit breaker show considerable wear on the main contacts and the arcing contacts, with phase A being the most damaged phase. This coincides with the phase that opens first, thus supporting the first-pole-to-open theory.

From the experience in the exploitation and the bibliographic analysis carried out [7] , the topic of selection of switches is of great importance, to avoid failures in the switches especially in the case at hand, the connection and disconnection of reactors or reactor banks, a process associated with the interruption of inductive currents that generate transient overvoltages of great magnitude with large frequencies [9] . Like the switches that are going to be installed near a generator, where the effects of the transient component of alternating current AC must be taken into account, analysis that is not the objective of the study [10].

Both practical and theoretical analysis have shown that the use of SF6 circuit breakers up to voltages of 34.5 kV is limited in the case of protecting reactors or reactor banks. Premature failures occur, shortening the circuit breaker's useful life. Although the literature proposes various solutions for these cases to reduce the rate of rise of the Transient Recovery Voltage (TRV), all of which entail additional costs in terms of equipment and system configuration.

Therefore, for the connection and disconnection of reactors or reactor banks, up to a voltage level of 38 kV, vacuum circuit breakers [11] must be used, since they have a greater capacity to withstand strong increases in the growth of the Transient Restoration Voltage TTR. For voltages greater than 38 kV, SF6 circuit breakers are recommended, due to the limitation that vacuum circuit breakers have with the chambers for those voltage levels [12]. But since SF6 circuit breakers are assigned, and the procedures applied are not adequate for this type of maneuvers, this procedure was proposed in the case study, to avoid catastrophic failures.

3.2. Preventive Maintenance Tasks for Switches that Operate Inductive Loads in Substations

Therefore, a maintenance plan different from that designed for conventional switches was implemented [13], since the degradation of the contacts has an exponential behavior $f(x) = e^{x}$.

Therefore, the following set of actions is carried out to guarantee the type of maintenance necessary for the optimal service of these switches that operate inductive loads [14], table 3.

Table 3. Preventive Maintenance Tasks for Switches that operate inductive loads in substations

Part to inspect.	That verify.	Periodicity of the intervention.
Poles (Gas).	- Pressure of the gas, nominal value. - Quality of the gas.	One year after commissioning, and then twice a year, until year four and then every three months thereafter.
Insulators/Poles.	-Absence of dirt on the surface.	Dependent on environmental conditions.
Connection of the primary terminals.	- Absence of corrosion. - Bolt torque/tightness. - Presence of fat on the unions.	One year after commissioning and once per year thereafter.
Grounding.	- Absence of corrosion on grounding borders. - Tightness of connections. - Presence of grease on unions.	One year after commissioning and once per year thereafter.
External transmission mechanics.	- Absence of dirt/corrosion on friction points. - Proper lubrication (grease) on moving parts	One year after commissioning and once per year thereafter.
External structure.	- Absence of corrosion. - Absence of loose screws.	One year after commissioning and every five years thereafter

Static and dynamics contact resistance.	- Static and dynamic contact resistance values. - Compare against factory/normative standards.	One year after commissioning and then twice a year until four years and then every three months thereafter.
Arcing Contacts.	- Measurement of contact wear/erosion. - Verification against manufacturer limits.	One year after commissioning and then twice a year until four years and then every three months thereafter.
Oscillograph	- Find out simultaneousness of contacts	One year after commissioning and then twice a year until four years and then every three months thereafter.

4. CONCLUSIONS

1. The analysis of a failed SF_6 circuit breaker used for switching a 34.5 kV reactor confirmed that the primary failure mechanism was accelerated contact degradation caused by high Transient Recovery Voltage (TRV) and its high rate of rise (RRRV) associated with inductive current interruption.
2. Standard preventive maintenance cycles, typically annual, are inadequate for breakers performing frequent inductive load switching. The deterioration follows an exponential trend, necessitating a condition-based maintenance approach with significantly increased monitoring frequency, as proposed in this article.
3. For medium-voltage applications up to 38 kV involving the switching of reactors, capacitor banks, or unloaded transformers, vacuum circuit breakers are technically superior to SF_6 breakers due to their higher TRV withstand capability and interruption characteristics.
4. Implementing a tailored maintenance plan focused on frequent contact resistance measurement and visual inspection of contact wear is essential to prevent unexpected failures, ensure reliability, and optimize the total cost of ownership for circuit breakers in this demanding service.

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