Substation Power Transformer Risk Management: Predictive Methodology Based On Reliability Centered Maintenance Data

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***Abstract* - The main objective of this article is to present details of a methodology for prioritizing actions in predictive maintenance substation equipment, applied to Power Transformers, which are responsible for the income revenue of energy companies (generation, transmission and distribution). This is one first immersion on the failure analysis and risk management with optimal use of predictive maintenance, to reduce or eliminate transformer outages. Using statistical concepts, this proposal goes through various stages of application, and addresses power transformer differences (generation, transmission and distribution), aspects of life cycle, operation, maintenance, aging, depreciation, aspects of reliability, risk of failure and effectiveness of predictive techniques. The basic process concept lays on stratification and consolidation of data from CIGRÉ Brazilian Working Group - Reliability Centered Maintenance, combined with historical information, taking also into account the diagnosis on equipment condition. Aiming greater visibility simulations is also presented using the methodology as exemplification for different characteristics of power transformers. Conclusions indicated that each company power transformer needs its own prioritization criteria, depending on the particularities of operation and maintenance history.**

Keywords – maintenance engineering, power transformer, predictive maintenance, reliability centered maintenance, transformer management.

I. Introduction

The substations represent indispensable functions in the energy generation, transmission and distribution. Be on voltage elevation for transmission over long distances, switching and voltage reduction for distribution, using in urban, residential and industrial. The substations concentrate complex equipments, essential to the power system. With the growth of unitary capacity, the operation of these devices requires today, a set of systems and support functions which include protection, reactive compensation, voltage and load control. It also requires insulation, supervision, etc., in addition to the basic function of processing, regulation and maneuver. This diversity, however necessary, multiplies the possible substations modes of failutres, including to those associated with the transformation, regulation, and switching functions.

Among substations devices, the power transformers, as shown in Fig. 1, represent the major asset investment and major concern regarding its maintenance and repair.

Figure 1. CPFL's Typical Distribution Power Transformer. Utility Distribution Brazilian Company. Typical Class Voltage and Rated Power: HV 36.2 to 145 kV; LV 15 to 25 kV; 5 MVA to 60 MVA.

Power transformers deserve, from managers and technicians, special attention regarding planning requirements, vendor qualification, design and specifications, acquisition process, factory and field testing, shipping, handling, operation, maintenance and design, materials, functions and performance diagnosis.

Nowadays there are various maintenance techniques to apply in the transformer operacional and maintenance cycle such as TBM – Time Based Maintenance; TBCM – Time Based Condition Maintenance; CBM – Condition Based Maintenance; OLCM – On Line Condition Maintenance. The maintenance strategy could be considered the combination of differents maintenance philosophies above and others [1].

To better manage risks involved in the transformer park, it is necessary to develop a methodology to guide managers and technicians, to support activities that improve failure diagnosis (and, when possible, predictions). This will support measures and actions that reduce the risk of critical failures, significantly related to this main asset, in order to keep it in proper operating conditions on an ongoing basis, using predictive maintenance practices or maintenance techniques based on Reliability Centered Maintenance (RCM).

The central idea of the methodology is to apply the best cost and effective techniques of maintenance, in terms of optimizing efforts between predictive maintenance and RCM. The goal is to expand maintenance scope and effectiveness, as much as possible performing simulations, along transformer history, going through its design features, passing through its real application conditions, and considering its relevance for

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the electrical system. It allows achieving an improvement in detecting more failure modes than it is usual today.

This paper aims to organize the ideas of the various functions listed above, to deepen the understanding and sensitization about diagnoses (and when possible predictions) with subsidies for measures and actions that can reduce the risk of critical and significant failures related to this asset in order to keep it in proper operating conditions permanently, using predictive maintenance practices. the ideal would be to remove from service before any failure (since there is no control on the fault and its implications to the professionals, general public, surroundings equipments and environment);

This methodology (prioritization, otimization, etc.) also contributes strongly as important subsidy in available analysis due to difficulties in establishing high level of investiment for small and medium power transformers (<100 MVA and < 230 kV).

II. Scenarios and Methodology

This study explores some scenarios of maintenance strategies emphasizing predictive maintenance, in adition to informations of risk management obtained from experience, including statistics of power transformer failures. Finally reliability centered maintenance concepts, structure and data that will be considered as a base to the present technical article adding two cases simulations.

The basic process concept lays on stratification and consolidation of data from CIGRÉ Brazilian WG - Working Group – Power Transformer RCM, combined with historical information, taking also into account the diagnosis on equipment by predictive maintenance.

Points to consider in the methodology should involve adequate transformer maintenance knowledge, risk management and eventualy monitoring systems depending on technical and economics analyses.

A. Maintenance Strategies

Maintenance can be defined as a series of actions (procedures, criteria, etc.) created for optimization of equipment, processes and budgets to achieve better maintainability, reliability and availability of this equipment. Executing maintenance not only increases reliability, but also causes the equipment to operate always close the rated factory conditions. There are conventionally three types of maintenance in primary level: predictive, preventive and corrective.

Predictive maintenance is the periodic equipment follow up, based on analysis of data collected from field inspection (visual inspection; main operational data reading; thermal inspection; partial discharges; analyses: chromatography, physical-chemical, furfural, particles and solid insulation moisture, etc.) [2][3][4][5][6]. Predictive maintenance is usually recognized as an effective technique for maintenance management.

Preventive maintenance is related to planed maintenance actions that prevent bad operation occurrences, even defect or failure. The conventional preventive maintenance programs include minor repairs, lubrication, adjustments, tests and functional tests. In this technique, the common denominator is the maintenance planning for a period of time and/or a predefined number of operations.

The corrective maintenance is not periodic and may variably occur. It is related to faults and defects in the equipment, and deals with not imminent damage, based on equipment knowledge evolution, field feedback and repair procedures, through opening and appropriate investigations (paper samples etc.).

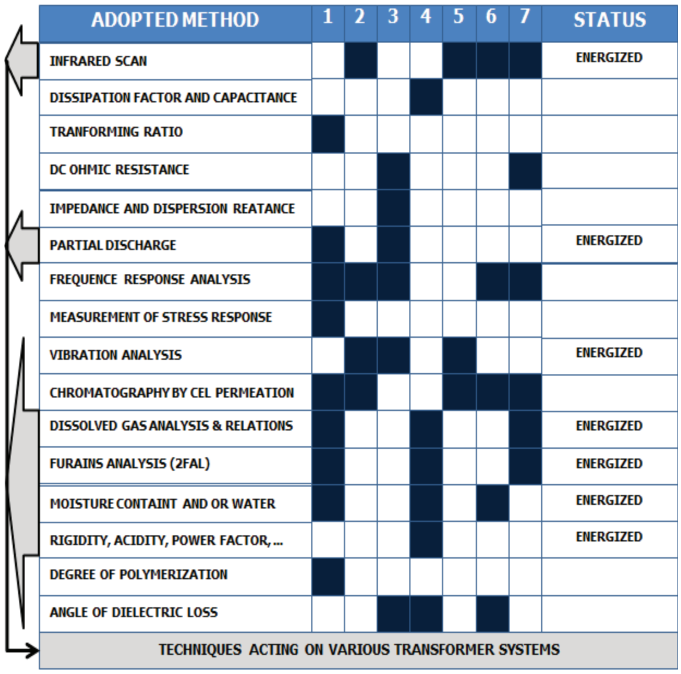

Figure 2. Trends in Predictive Maintenance Techniques (Adapted from CIRED, Italy 2006)

However, the maintenance function has a broader and deeper concept, hence reaching equipment and facilities integrity. Further analysis and reflection are needed about other relevant issues such as:

- Available resources – materials, tools, human resources, budget, etc.;
- Environmental constraints – traffic access, climate, regions, etc.;
- The importance of facilities – transmission, distribution, mash grid, etc.;
- Characteristics – radial, short circuit level etc.;
- The application status and functionality of the equipment – age, function, family use, parallelism, etc;
- The history of defects (failures) in maintenance services for each equipment (records, statistics, trends, etc..); and
- The ongoing interaction with other areas directly or indirectly involved – planning, design, construction, operation, supply chain, etc.

Trends in maintenance techniques based on traditional measurement and diagnosis, as shown in Fig. 2, are used individually or combined among them. The problems in the main types of defects referred to transformer systems are the following:

1. Solid insulation – excessive moisture, aging;

2. Magnetic circuit – core compression, contact fittings, partial discharge;
3. Windings – warping, loss of shims, deformation;
4. Oil condition – oxidation, aging, saturation;
5. Cooling system, treatment and protection – (fans defects, inherent devices failure;
6. Bushings – electrical discharges, partial discharges, ground reference loss; and
7. Tap changer and voltage regulation – fatigue, excessive torque, melting, damage.

In addition, a maintenance policy used to minimize faults or defects consequences in severe outages is to keep a strategic minimum transmission equipment reserve, especially useful in case of high level of standardization equipment. These equipments are supplemented by mobile equipment (substations, transformers, breakers) stationed in carefully chosen locations with the necessary number of parts. They allow recovery time up to four or eight hours.

There is also, in relation to the maintenance, complementary conventional measures by means of medium and long term alternatives, such as electric system expansion plan (vegetative and overruns) and improvement efforts on existing facilities. In any case, special plans are formed by a series of consolidated actions looking for incorporating more synergy to the processes (ten-year improvement plan; substation equipments repair services by specialized and qualified supply; climate data, etc.).

B. Risk Management Scenarios [2]

Despite all the efforts and strategies adopted, the 145 kV class CPFL power transformers have failures rate up to 1.5%, accumulate failures rate, being in relative stability. Older equipment that, despite not having high failure rate, deserve special attention due to the lack of spare parts, technical support, manufacturer no longer existent, leakage reduced level, outdated manufacturing technology, etc. (Fig. 3). The Operation WG transformers data have failures rate: active 14.9%; tap changes 27.7%; connecting 10.9%; supervision 32.5%; protection 2.1%; structural 5.9%; oil preservation 4% and cooling 2%.

The logic of failure in transformer explosion followed by fire or not (Ronningen, Ignition Handbook), has incorporated new parameters that must be taken into consideration in case of failure analysis and definition of transformers management strategies.

Preventing catastrophic failure also involves knowledge, elimination or reduction of the considered chronic influence of problems over the years (parts and accessories). Some of them historically are the following: the 70's high-voltage bushings oil impregnated paper; the 80's high-voltage bushings resin impregnated paper; the 80/90's "filterless" on load tap changer; transformers with tertiary inadequate design; excessive request from power systems operation features, as short circuit level; corrosive sulfur, especially in generation and transmission power transformers and reactors.

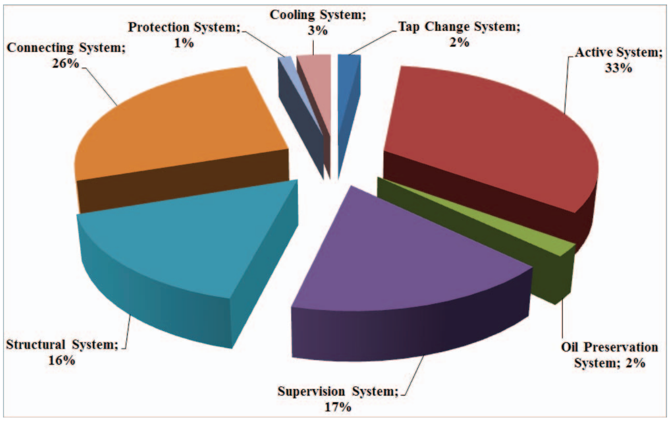

Figure 3. Typical Failures Rate in Distribution Power Transformers (CPFL Data, 2010)

Moreover, some important observations from experience suggest the following inferences:

- High severity defects with the full combustible gases slow evolution average, are detectable. But, it is not possible to predict the date of failure with extreme precision;
- Usually there is no insurance compensation in case of withdrawal by evolution of gases – preventive maintenance;
- Tertiary use in autotransformer increases the risk of packaging due to system faults, specially when it is used also for auxiliary services;
- Paralleling transformers increases dynamic solicitations (short circuit levels, mechanical stress, etc.), and,
- Generation, transmission and distribution equipments have different requests during operation.

Additional causes can be described as the main points:

- Interference of chronic problems in the recent past;
- Lower safety margin in design, construction and use;
- Not known electromagnetic phenomena still in research;
- Limit overrun in operation and system capacity;
- Increasing handling of assets;
- Poor commissioning or shortness of test appropriate requirements;
- Unsuccessful, inadequate or not performed preventive maintenance;
- Accelerated aging referred to installation or heavy operation condition and vandalism.

The difficulties in visualizing incipient failure may be related to the following relevant points:

- No possibility of sudden failures diagnosis and prognosis;
- Failure of rapid evolution in the period between oil samples for chromatography analysis;
- Long periods between off-line chromatography tests;

Another approach is to establish an index of reliability (or risk of failure) of equipment in relation to factory inspection tests. A case study at CPFL Energy (a large Distribution Electricity Utility in Brazil, founded in 1912, now with 7 million costumers, 535 cities, 350 substations, 500 power transformers and peak demand around 6,000 MW, , had a history of occurrences in 424 tests (routine and type) to 90 transformers in the period from 1980 to 1995 [2].

This led the company to develop action plans to overcome the situation (monitoring manufacturing processes). This is corroborated by more recent data in 2011, presented in [2] in which on other large Transmission and Generation Electricity Utility in Brazil, among 70 transformers and reactors > 345 kV produced in the period 1996 to 2006, at least 27 units had failures in factory tests, and 18 failed in operation.

C. Reliability Centered Maintenance Data Base

The present article approach is focused on technical aspects. The incorporation of economic and financial aspects referred to transformers life expectancy was approached in a previous study [7]. That is a highly complex matter since it involves power transformers operational parameters in a situation of normality or abnormality.

Identifying and studying all the transformers failure modes are complex, and require a considerable effort of those responsible for maintaining, designing and manufacturing them. It is not always possible to get into a so deep degree in analyzing them in companies that use small and medium power transformers (< 230 kV and < 100 MVA) due to limitations of economic feasibility [8].

Traditionally, the analysis of failure modes and their effects have been recommended as an ideal method to catalog and analyze the consequences of failures in complex systems. Besides identification, it must be also defined what kind of action is recommended to prevent from or correct the failure, or minimize its consequences. Both goals are achieved only by adopting a structured methodology, which correlates each failure mode with the preventive confrontation activity [8].

Among the contemporary maintenance methods, RCM stands out as an integrated set of tools to identify and analyze all plant failure modes, suggesting corrective or preventive actions to minimize failures impact. In addition, RCM is characterized by prioritizing strict safety procedures and environment preservation, to ensure its economic attractiveness. Qualitative methods for selection of maintenance activities are systemized in the RCM, and standardized by international associations (IEC, ISO and ANSI). The main definitions adopted by the RCM, as a result of recent studies and research conducted by CIGRÉ Brazil [8] [9], are briefly described in subsequent items.

The methodology aims to make a major consolidation among the data obtained from studies and analysis focused on transformer maintenance quality and risk management. Finally it settles a strategy for providing a prioritized organized list of equipment to be maintained according to their importance for the electrical system.

In a succinct way, the main concept of area refer to their own universe, in the definition of facilities, systems, components, functions, types of failure, failure modes, causes, effects of failure modes, criticality in the assessment of failures and culminates with the composition of a failure maintenance plan using operational, environmental and economic criteria [8].

There are eight basic systems identified [8] as typical in most liquid insulated transformers - oil immersed, (Fig. 4):

- Tap Changes System
- Active System
- Supervision and Control (eventually Monitoring) System
- Oil Preservation System
- Protection System
- Structural System
- Connecting Facilities System
- Cooling System

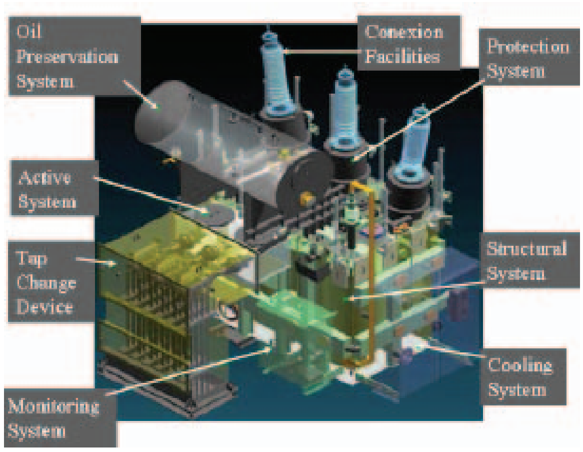

Figure 4. Power Transformer Related Systems (CIGRÉ, RCM Brazil 2006)

Only transformers with on-load tap-changers are included in this approach. The other systems are common to most transformers immersed in insulating liquids, although other names are possible [8].

The data evaluated come from 275 components (oil level indicator, gas relay, etc.), 184 functions (all failures correspond to some funtions), 406 types of failures (comprise the installation), 1436 modes of failures (associated to components). Next step was the classification of the criticality of failures (catastrophic, critical, marginal, minimum and negligible), then faults were estimated 640 critical, 750 major and 46 minor. Each failure mode was defined (operational service, predictive, etc.) and criteria for applicability and effectiveness for each type of maintenance activity in eight typical systems of transformers. It was found an absolute preponderance of predictive maintenance techniques (50%) of failures modes and other information related to criterion, distributing frequencies and company procedures [8].

The relationship between failures modes and functional is recorded by a correlation matrix for each system function and component installation. Each row of this matrix identifying a failure mode that is associated with related functional faults of the matrix in columns for each system function and the component installation. Every indication in the matrix cell means that the failure mode of the line causes the functional failure listed in the column. The end has a summary of the number and percentage of failure modes identified in each of eight typical of most transformer systems [8].

The final result of RCM work is a maintenance plan for the power system, organized by transformer system and activity. For each system, activities are identified and suggested. The frequency of each activity on a system is calculated by the higher frequency (or shorter interval in hours) for each of the suggested components of the system. The frequency of each activity in each component is calculated by the higher frequency (or shorter interval in hours) of each failure mode of the component for which it was suggested that activity. RCM is usually applied by means of computational support due to many involved variables [8].

III. Analysis and Results

The analysis of maintenances strategies, RCM and risk manegment scenarios, related to predictive techniques, taking into account the same weight for all systems corresponding to the components, functions, failures, failure modes and criticality level, it can be concluded that the impacts and their stratification [2] (Impact Column – normalized total relation between quantities parameters) would be according to Table I.

TABLE I. Parameters Stratification
(CIGRÉ, RCM Data, Brazil, 2006, expanded)

Designation	Components	Functions	Failures	Modes	Critical	Impact
Tap Change System	70	38	80	342	137	75.23%
Active System	29	33	74	122	111	7.24%
Supervision System	45	43	106	231	26	9.09%
Oil Preservation	29	24	49	200	134	7.01%
Protection System	22	10	40	135	61	0.55%
Structural System	23	14	26	136	53	0.46%
Connecting System	34	8	16	123	62	0.25%
Cooling System	23	8	15	147	56	0.17%
Total	275	178	406	1436	640	100%

Taking into account the same weight for all systems corresponding detectable predictive tests (chromatography, visual, thermography, etc.), it can be concluded that the impacts [2] would be according to Table II (Detectable Column – predictive prospective range using actual utility tools avaiable). The efectiveness of predictive ations is showed on Table III (Effectiveness & Not Effective Column).

Furthermore confronting in the preliminary tests effectiveness of the predictive with the current occurrences (CPFL database from 2000-2010), it can be concluded that we have transformer vulnerabilities to be exploited predictively, assuming all failures identified and known and subject to the same conditions. As additional simulations one can see the Brazilian Operation Work Group (1998) failures data [13].

As a result, predictive maintenance in power transformers without removing operation, etc. [9][10] [11] [12] participate in the definition of 52% of detectable failure modes.

TABLE II. Predictive Range Behavior
(CIGRÉ, RCM Data, Brazil, 2006, adapted)

Designation	Research	Predictive Range		Detectable
Tap Change System	84	46	54.76%	11.94%
Active System	80	41	51.25%	11.18%
Supervision System	179	75	41.9%	9.14%
Oil Preservation	141	107	75.89%	16.56%
Protection System	110	26	23.64%	5.15%
Structural System	16	15	93.75%	20.44%
Connecting System	95	64	67.37%	14.69%
Cooling System	84	42	50.00%	10.9%
Total	789	416		100%

TABLE III. Efectivness of Predictive Actions
(CIGRÉ, RCM Data, Brazil, 2006, adapted)

Designation	Impact	Detectable	Efectivnees	Not Efective
Tap Change System	75.23%	11.94%	75.10%	3.56%
Active System	7.24%	11.18%	6.77%	13.32%
Supervision System	9.09%	9.14%	6.95%	13.26%
Oil Preservation System	7.01%	16.56%	9.71%	12.90%
Protection System	0.55%	5.15%	0.24%	14.26%
Structural System	0.46%	20.44%	0.79%	14.18%
Connecting System	0.25%	14.69%	0.31%	14.25%
Cooling System	0.17%	10.9%	0.15%	14.27%
Total	100%	100%	100%	100%

Assuming that all utilities use the same predictive testing procedures, and that these procedures are the only faults diagnosis avaiable (used in their fullness, with equal importance weights and healthy equipments), the relevant points can be seen in Fig. 5 Operation WG, compared to what was expected (blue arrow). The defects refer to:

- Tap changer system (gap ~ 7.0 = 28/4);
- Supervision system (gap ~ 2.93 = 33/13), and
- Active system (gap ~ 1.16 = 15/13).

The points presented in Fig. 5 CPFL Data compared to what was expected (red arrow) are the following. On load tap changer incorporate to power transformers is a relatively new device in CPFL (since 1990's). The defects refer to:

- Active system (gap 1 ~ 2.48 = 33/13);
- Connecting system (gap 2 ~ 1.82 = 26/14), and
- Supervision system (gap 3 ~ 1.27 = 17/13).

Qualitative analyses show that Operation WG transformers data, tap changes systems need 2.3 and 5.8 times more attention (predictive tools) than supervision and active systems. For CPFL transformers data presented, active systems need 1.4 and 2.0 times more attention than connecting and supervision systems.

For the last case pointed above, for instance, many actions can be done to mitigate the problems with active system (chromatography analysis on line); with connecting system (buchings sensor to evaluate the levels of capacitance, pressure, power factor and partial discharges as well); and with supervision system (improvement the actual systems quality and withstand to electric and magnetic interference).

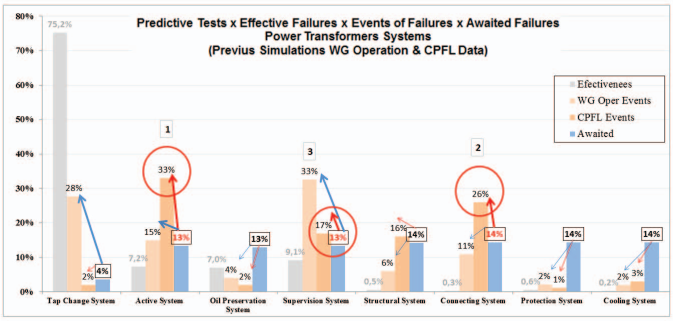

Figure 5. Relations: Predictive Maintenance Techniques & Effectiveness & Expected Defects & Current Events (Exemplification: CIGRÉ, Brazil, 2006 RCM Concepts, Operation WG Data 1998 and CPFL Data 2010)

In other words each company has a profile involving failure modes of their transformer systems (dynamic characteristic), which can be applied in accordance with the importance (weights) for each type of failure as a result in assessing risk or optimizing resources advancing in the proper direction.

It can be also reflected on the use of other predictive maintenance as a fundamental tool, provided that they can add value (analysis of technical and economic feasibility).

IV. Conclusions and Next Steps

From maintenance information of Brazilian utilities based on a research by Working Group, CIGRÉ, with focused on RCM of power transformers, plus distribution utility real statistics events data, completed with main data and maintenance assessment trends, a research was made. A stratification of points considered relevant and observed pertaining boundary conditions, made it possible to compare two different patterns.

Aiming greater visibility it also presented simulations using the methodology as exemplification for differents characteristics of power transformers.

In spite of a preliminary stage, confront of results, the effectiveness of predictive testing and the current occurrences, and assuming all faults known and identified as subject to the same conditions, it can be inferred that there are vulnerabilities in the transformers. One of by-products refers to catalyze efforts directioned to the right target, what depends of electrical system envolved.

Thus, one of the main findings is a continuing need for developing predictive maintenance techniques and devices (portable, robust with massive data storage), without transformer deenergization, with knowledge dissemination, to provide quick and conclusive diagnostic (maybe prognostic), with the appropriate manufacturer technical support.

It is noteworthy that this applied predictive maintenance does not preclude nor replace conventional scheduled preventive maintenance for each type of substation equipment based on maintenance programs and/or predictive signals.

These arrangements require coordinated and integrated action of different specialties (engineering, projects, planning, operation, maintenance, asset management and purchasing / contracting), taking into account the strategic importance of the substations, and associated equipment.

It creates a series of opportunities for future research, even in a primary level, in order to improve and advance the present study using alternative techniques like analitic hierarchy process specially obtaining costs and benefits simulations with new tools applied to predictive maintenance.

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Biography

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