APPLICATION OF GREEN LEAN SIX SIGMA FOR MAINTENANCE MANAGEMENT OF ELECTRICAL EQUIPMENT IN TRANSMISSION SUBSTATIONS

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The new legislative requirements lead to changes in life cycle costs and implicitly to the reduction of the life span of electrical equipment. The most efficient maintenance methods are also the most expensive, for this reason it's necessary to introduce a new method. Green Lean Six Sigma (GLSS) is a technique used in asset management, which offers the necessary tools to decide, implement and support improvements that have a positive impact on the environment. The purpose of this paper is to highlight the necessity and opportunity to implement the concept of Green Lean Six Sigma for asset management in high voltage electrical substations, as well as the feasibility of this goal. The aim is to expand the reliability centered maintenance method from a 2D analysis to a 3D one. A solution to improve substation maintenance is proposed by generating a global priority index of maintenance activities.

Keywords: life cycle, Green Lean Six Sigma, global priority index of maintenance activities, maintenance management, power substations

1. Introduction

Aging assets management is a challenge for transmission and system operators. Since the assets exceed the estimated lifetime, an analysis is necessary from the point of view of the causes of degradation, the evaluation of the lifetime and its extension. Understanding aging allows making decisions about equipment management and detecting more efficient risk management techniques related to equipment failure [1]-[3].

The optimal management of the lifetime of the assets is essential to fulfill the objectives of a company [14]-[18]. Lifetime management decisions include: equipment management in case of failure, failure prevention; identification of the activities for determining the degree of aging, the influencing factors that lead to aging; anti-aging activities; implementation and continuous monitoring of the performance of electrical equipment. As a result, the maintenance of electrical equipment has become a task in planning their life cycle [8], [10], [12], [13],[19].

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The most effective maintenance methods are also the most expensive and therefore cannot be used in every situation. A maintenance service always includes many objectives that must be met and it also requires the existence of adequate stuff. During the development of maintenance and management concepts, a series of flexible methods, tools and techniques were introduced in order to obtain the greatest possible financial savings.

The Lean concept was adopted by large companies to reduce waste, and Six Sigma was introduced to identify and eliminate faults. Many researchers [4]-[7] recommend the use of the two methodologies due to the common bases: origin, application criteria, concepts, objectives, targets and the application of project management. However, there are risks related to the implementation of Lean Six Sigma (LSS) that if they are not managed properly can lead to the failure of a project.

Due to the limitations of LSS and the legislative requirements related to the environment, a new concept, Green Lean Six Sigma (GLSS), was introduced for efficient decision-making related to the environment. This methodology uses the DMAIC (Define, Measure, Analyze, Improve and Control) approach to achieve environmental objectives within a company.

This paper is intended to be a contribution in the field of maintenance management of power substations and to highlight the fact that the complex problems faced by the maintenance department can be solved by implementing the proposed methodology.

The paper is divided into 5 chapters. The first chapter presents a brief introduction to the theme of the paper. The second chapter describes the management concepts and approaches for extending the life cycle of power substations. Chapter 3 presents the concept of GLSS in the different phases of the Define, Measure, Analyze, Improve and Control (DMAIC) method to highlight how maintenance contributes to the life cycle cost value. In chapter 4, a practical study is presented on the opportunity to extend the life cycle of electrical substations through the GLSS approach within an electrical transmission substation.

2. Management concepts and approaches

The management of the maintenance of electric substations requires the use of decision support systems for the organization of maintenance activities and costs [17]. Most transmission and distribution operators maintain an effective computerized maintenance management system (CMMS). It can be used to program, plan, monitor and perform asset management [8], [9], [13].

A well-managed CMMS enables transmission and distribution companies to pursue maintenance cost reductions as follows:

- provide appropriate indices to assets to minimize the risk of faults;
- provides useful information to allow the analysis of the main cause of the occurrence of fault and the trends subsequently applied;
- enables more precise management of resources, which enables asset managers to make better decisions;
- establishing a mathematical model based on costs, which allows the optimization of maintenance activities. The mathematical model must take into account the information about active resources, as well as the data from the CMMS;
- provides a solid basis to select activities that are not economically efficient or do not have available resources;
- allows the optimization of labor management, both within the company and external contractors.

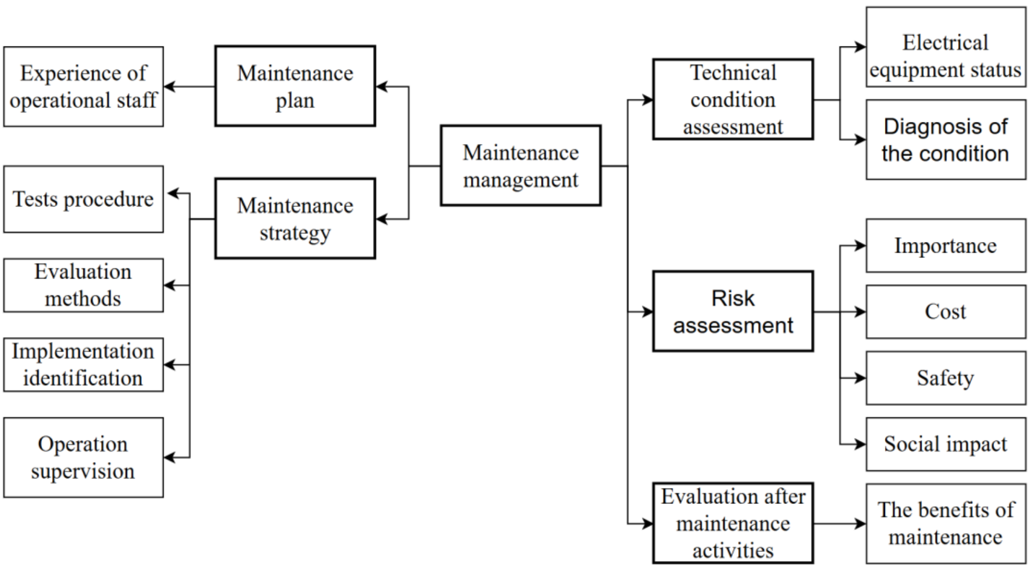

Fig. 1. The objectives of maintenance management

Maintenance management objectives can be divided into levels (fig. 1). Thus, it must be taken into account that during the operation, evaluations of the technical condition of the electrical equipment should be made. Risk assessment is another step that must be implemented for the timely replacement of a component. After carrying out the maintenance plan and applying the appropriate maintenance strategy (established based on tests, evaluation methods and fault detection), an evaluation takes place to determine the effect of maintenance on the technical condition of the equipment.

3. Green Lean Six Sigma methodology

Green Lean Six Sigma is a concept approached as a result of the limitations in terms of environmental impact of Lean and Six Sigma methodologies. Lean Manufacturing helps to reduce waste that could indirectly contribute to environmental performance, and Six Sigma tries to completely eliminate faults. GLSS includes ecological techniques to achieve the goals of sustainability, social development, minimization of operational costs, conservation of resources and takes into account government policies. In fig. 2 the advantages and particularities of GLSS are presented. Studies [4], [6], [11] show that by using the DMAIC approach, an increase in environmental performance between 11-20% can be obtained. GLSS tools used in different phases of the DMAIC approach to achieve environmental performance [4]-[6] are: LCA (eng. Life Cycle Assessment), DOE (eng. Design of Experiment), SPC (eng. Statistical Process Control), VSM (eng. Value Stream Mapping) and Pareto analysis.

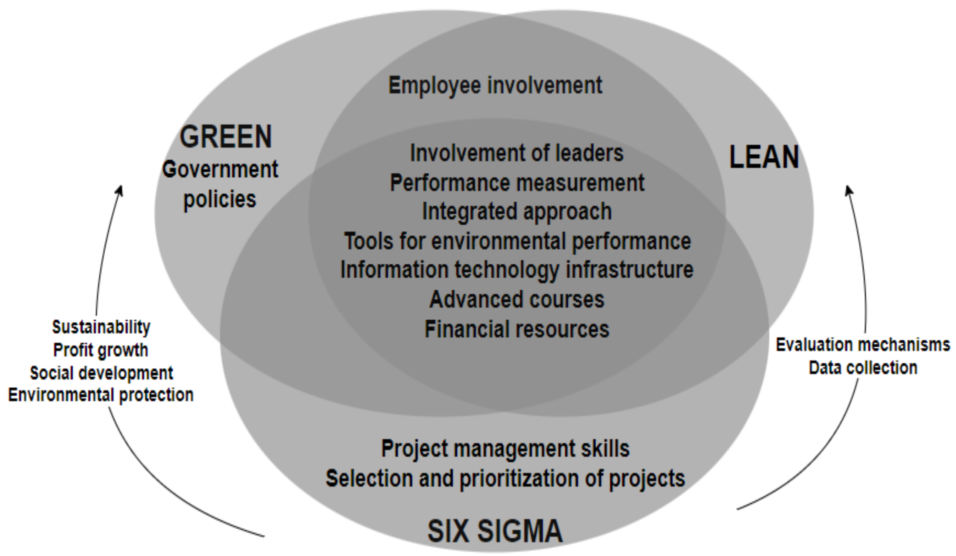

Fig. 2. Advantages and particularities of GLSS

The integration of GLSS in the paper is implemented by going through the 5 phases of the DMAIC process [6], [7] (fig. 3):

- **Phase 1 GLSS: Define.** In this phase, the purpose, scope, identification of problems, environmental restrictions and their financial impact are identified.
- **Phase 2 GLSS: Measure.** In the measurement phase, information is gathered, appropriate data collection methods are developed, reliable measuring devices are identified for monitoring key points.

- **Phase 3 GLSS: Analyse.** In this phase, its necessary to find the causes of the problems, check if the measures taken are correct or need to be redefined and identify the necessary actions to optimize the process.
- **Phase 4 GLSS: Improve.** Solutions are generated and implemented to solve the problems identified during the analysis stage. Waste reduction strategies are integrated.
- **Phase 5 GLSS: Control.** The phase monitors and confirms the implemented improvements. After this phase, decisions can be made and the next necessary actions can be planned, ensuring the sustainability of the results.

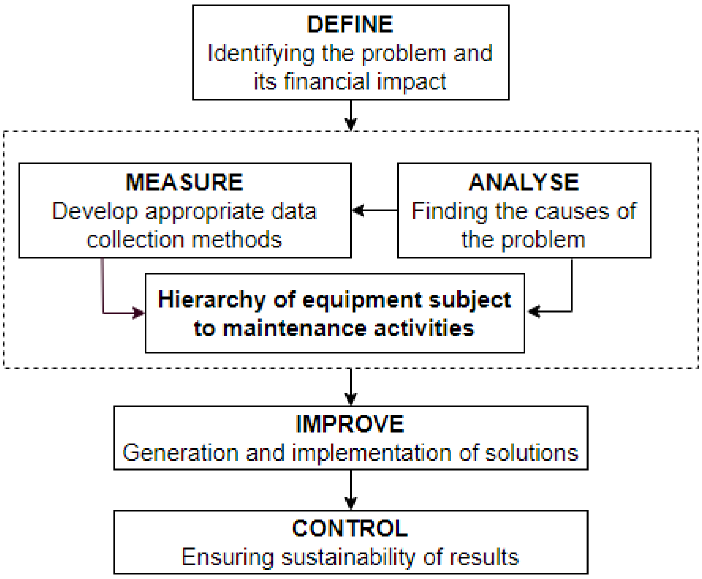

Fig. 3. GLSS phases

4. The application of GLSS within an electrical transmission substation

For the application of the GLSS concept, a power substation, 220/110 kV (fig. 4) within the transmission grid, located in the central area of Romania, is considered.

The 220 kV substation has the role of power evacuation from two hydroelectric plants. The 220 kV substation is an outdoor type, each power line and autotransformer is connected by 2 and 3 couplers (CT), respectively, forming the 6 bus bars (nodes) of the substation.

The 110 kV substation is an outdoor type with two busbars and consists of 10 power lines. The interconnection between the 220 kV and 110 kV substations is made through two power autotransformers AT1 (200/200/60 MVA) and AT2 (200/200/60 MVA).

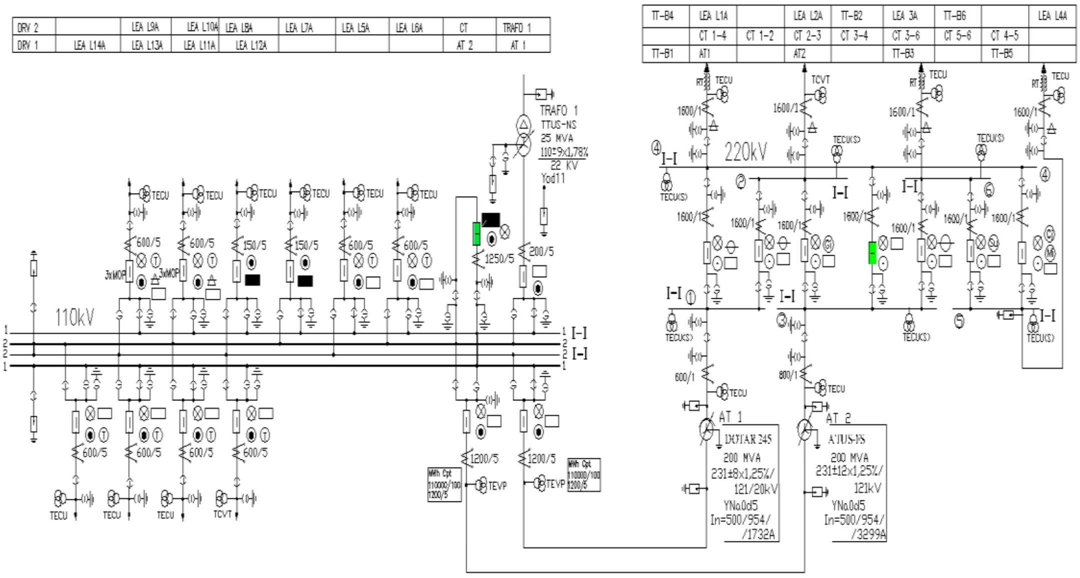

Fig. 4. Single line diagram of the power substation, 220/110 kV

4.1. Phase 1 GLSS: Define

The purpose of this phase is to provide the maintenance manager with a working alternative to be used to increase the life cycle of a power substation by considering all life cycle stages.

Restrictions: Performance standards, that electrical equipment must comply with.

Solutions: digitized substations; new substations, located right in the load consumption center to limit power and electricity losses; flexibility in transited electric power control systems.

The data collection methods help in the stability and realization of equipment evaluation questionnaires based on the analysis of the technical, economic, environmental and occupational safety consequences that the failure of each equipment can have. They will take into account the procedures and norms for checking and measuring the main parameters, the values resulting from measurements and tests, to which the experience of operative staff is added.

4.2. Phase 2 GLSS: Measuring the technical performances of high voltage equipment

The measurement phase includes information gathering as well as analysis of existing data extracted from monitoring systems. Identification of potential design or commissioning failures is done using FMEA. This phase includes the use of advanced measurement tools to identify factors that affect the technical performance of high voltage equipment.

The case study within the paper focuses on the analysis of the circuit breakers within the considered power substation. The analysis can also be extended to disconnectors, current and voltage transformers and arresters.

Short-circuit current, dielectric stresses, number of operations and mechanical loads are the main factors affecting the operation of circuit breakers, as well as environmental stresses (ambient temperature, humidity, UV radiation, earthquake/vibration, etc.). The number of operations is considered the most important factor.

4.3. Phase 3 GLSS: Analysis of the impact of high voltage equipment failure on the performance of the substations

The stage checks if the measures applied correspond to the expected ones. The maintenance process of power substation assets was examined and all operations and activities directly and indirectly associated with maintenance were analyzed with GLSS methodologies.

The equipment evaluation criteria are used to determine the indices (technical condition, importance, environmental protection, health and safety) necessary to make a ranking of the equipment. Each type of equipment has a specific set of performance criteria. There are criticality rates (scores) for indices of technical condition and importance, from 1 to 5. Most assets assessed will be in groups 1 and 2. This means that the equipment does not require any specific remedial action at the time of assessment. Those in groups 3, 4 and 5 should have an individual action plan based on the identified failure mode, overall rate of progression and exposure to criticality.

(1). **Technical condition index**

The criteria used to evaluate the technical condition index can be: operational experience, visual inspections or the results of measurements and monitoring. By multiplying the scores obtained by an equipment for each of the criteria, the technical condition index is obtained (i_{st}):

$$i_{st} = \prod_{n=1}^{5} Criterion\ n; \quad (1)$$

(2). **Importance index**

The importance of equipment can depend on: technical aspects, social and legal aspects, financial aspects, impact on the environment, workplace safety, occupational health, etc. By multiplying each score obtained from a equipment, the importance index is obtained (i_{imp}):

$$i_{imp} = \prod_{m=1}^{5} Criterion\ m; \quad (2)$$

(3). **Environmental protection, health and safety index**

In this case, the evaluation of scores is done from 1 to 7 for the most likely consequences of some breakdowns, at the equipment level of an electrical substation, on occupational health, stuff operational safety and the environment. By multiplying each score obtained from a equipment, the environmental protection, health and safety index is obtained(i_{mss}):

$$i_{mss} = \prod_{s=1}^{7} Criteriu\ s; \quad (3)$$

Based on the data obtained from the measurements, as well as those taken from the monitoring systems, each evaluation criterion can be assigned a score based on questionnaires to evaluate the technical condition, the importance and the impact of the failure of the electrical equipment on the health and safety of the staff and the environment. For each circuit breaker within the electrical substation under analysis, indices are calculated. Fig. 5 and fig 6 illustrate the results obtained.

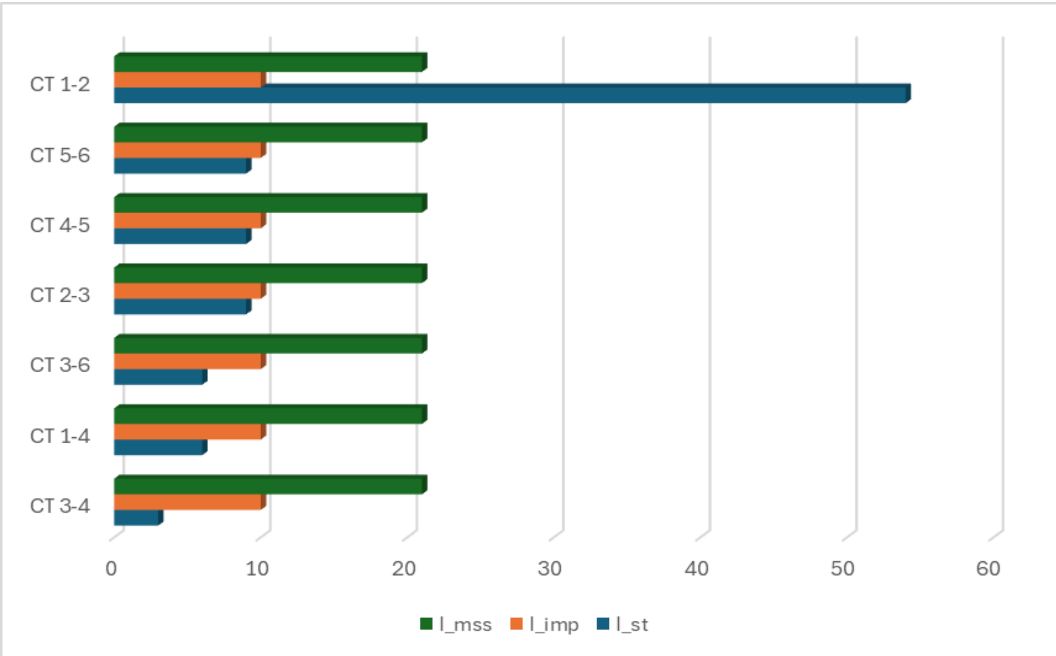

Fig. 5. Comparative graphical representation, for circuit breakers of 220 kV substation, of the index values calculated based on the assigned scores

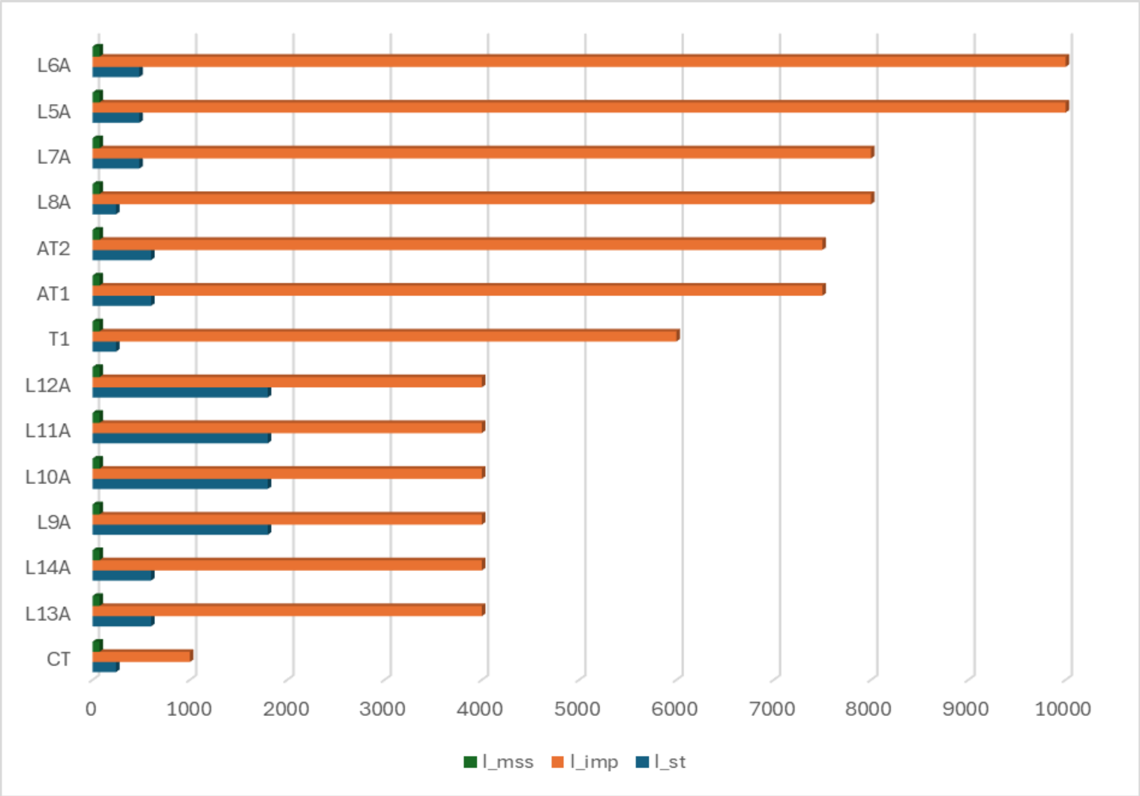

Fig. 6. Comparative graphical representation, for circuit breakers of 110 kV substation, of the index values calculated based on the assigned scores

4.4. Phase 4 GLSS: Improving the maintenance management of high voltage equipment

The purpose of the phase is to identify, implement and monitor the solutions adopted during the analysis phase. Based on the analysis of the technical condition of the equipment, its importance and the protection of the environment, health and safety of the operative staff, it is proposed to correlate the three indicators and calculate a **global priority index of maintenance activities** (i_g). The general expression is:

$$i_g = \sqrt{i_{st}^2 + i_{imp}^2 + i_{mss}^2}; \tag{4}$$

The results can be represented in an x-y-z coordinate system as in Fig. 7. On the ox axis is the technical condition index of the equipment (i_{st}). On the oy axis is the importance index of the equipment in the electrical network (i_{imp}). On the oz axis is the environmental protection, health and safety index (i_{mss}).

For each coordinate point (i_{st}, i_{imp}, i_{mss}) a global index (i_g) will result.

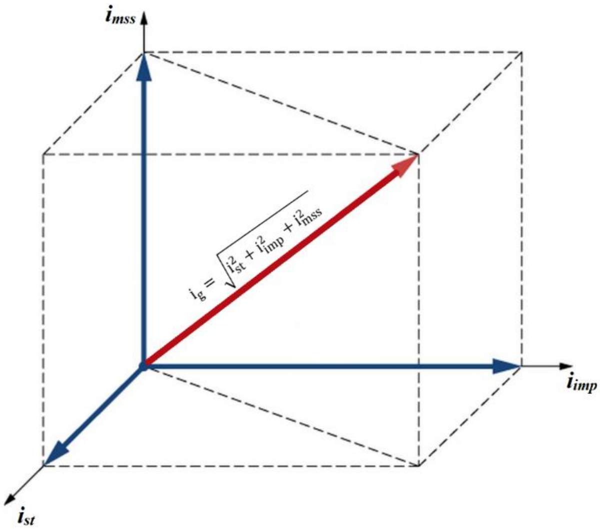

Fig. 7. The principle of determining the distance d in the priority diagram

Establishing the priority of maintenance activities will be done according to the distances d in the priority diagram. For each equipment, a distance d_k is calculated, with k = 1...n, where n = no. the equipment. The comparative analysis of the size of the distances d_k determines the order in which the equipment will be subjected to maintenance activities. Electrical equipment that has the largest dk distances will have priority.

4.5. Phase 5 GLSS: Control of the results of previous phases for continuous improvement

First, the importance of the electrical equipment was controlled and analyzed according to its technical condition, in order to estimate the level of maintenance impact (low, medium, high) on reducing the risk of failure. The environmental impact of the equipment was then tracked based on its technical condition as well as its importance for the equipment to fulfill its role within the transmission grid while meeting the specification criteria, including environmental requirements.

4.6. Results and discussion

By analyzing the results, forecasts and decisions can be made and maintenance actions can be planned. Depending on the value of the global index, a classification of the necessary maintenance activities is made, as follows:

- $i_g \in [0, 50)$ – normal operation;
- $i_g \in [50, 1000)$ – technical inspections;

- $i_g \in [1000, 5000)$ – minor maintenance;
- $i_g \in [5000, 10000)$ – major maintenance;
- $i_g \geq 10000$ – replacement of components/equipment.

Based on the above classification, the graphs in figures 7 and 8 were made in Matlab to highlight the circuit breakers within substation (220 kV, respectively 110 kV), which exceed the limits of safe operation, as well as the activities that will be applied depending on the value of the global index.

Analysing figure 8, most of the circuit breakers are inside the half-sphere that defines normal operation, and only one circuit breaker is outside it, which means it will need further inspection. Regarding 110 kV substation (figure 9), the values of the global index are much higher and for this reason 3 half-spheres were built: the first half-sphere covers the equipment that needs technical inspections (ig < 1000), the second half-sphere deals with the circuit breakers for which ig ∈ [1000, 5000) and which require minor maintenance activities, and the third half-sphere establishes the equipment that is prioritized from the point of view of the need for major maintenance activities. It is noted that category VIII of circuit breakers have a global index value greater than 10000, which leads to component replacements or even equipment replacement.

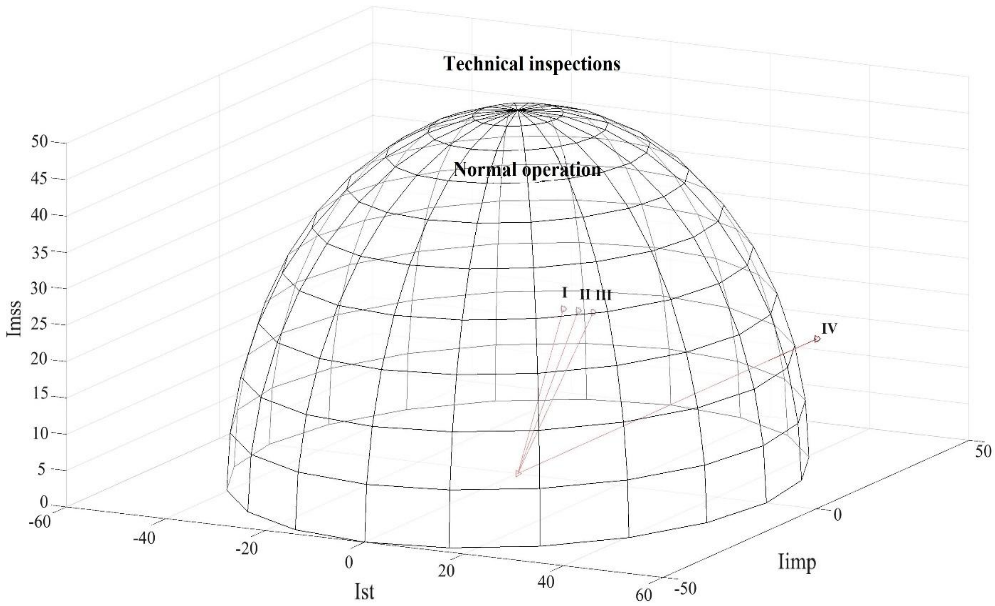

Fig. 8. Ranking of maintenance activities according to the value of the global index for circuit breakers in 220 kV substation

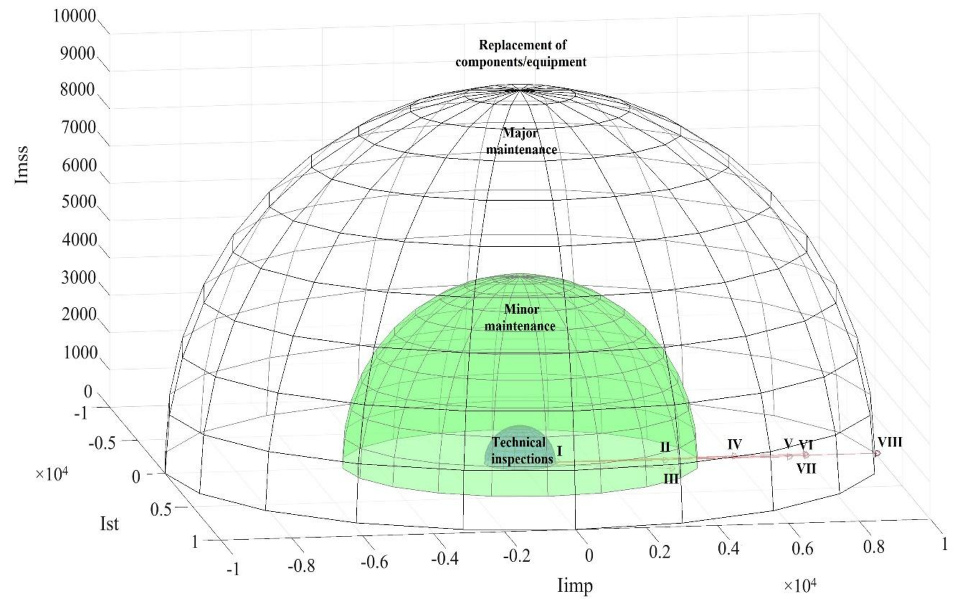

Fig. 9. Ranking of maintenance activities according to the value of the global index for circuit breakers in 110 kV substation

5. Conclusions

The paper proposes risk assessment and management and identifies a new methodology, Green Lean Six Sigma, which uses aspects of traditional Lean and Six Sigma methodologies, while providing the necessary tools to improve environmental impact. It is noted that the influence of the environment throughout the life cycle is partially or inadequately covered in equipment standards. Therefore, it is challenging to understand equipment capacity and aging in response to environmental demands over their life cycle, sometimes over 40-50 years.

The Green Six Sigma methodology is explained and then applied to circuit breakers within the 220/110 kV substation. The problem was formulated, constraints were identified, and methods of data collection for design, construction, commissioning, operation, and maintenance were established. The measurement points and devices used to highlight how maintenance contributes to LCC have been established.

The objective of measuring/monitoring and collecting data from circuit breakers was to identify the main factors that affect technical performance and analyze the consequences of their failure.

The power substation asset maintenance process was examined and all operations and activities directly and indirectly associated with maintenance were analyzed for process improvement. The proposal of a solution to improve substation maintenance by generating a global priority index of maintenance actions had as its objective the implementation and monitoring of the solutions adopted during the analysis stage.

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