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Reactive power compensation considering a maintenance management model in an industrial plant

Compensación de potencia reactiva considerando un modelo de gestión de mantenimiento en una planta industrial

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Abstract

Nowadays, the development of electrical systems implies addressing issues of profitability in their processes, where decision-making aimed at energy efficiency without considering possible impacts on certain risks that can present high unprofitable costs for a plant. Integration of energy efficiency, maintenance and asset management is important for organizations. This work shows a case study where a reactive power compensation problem is presented, through the analysis from a maintenance management model aligned with an asset management. The application of different technical indicators of maintenance, reliability and economic management related to electrical parameters such as they are; active power, reactive power, apparent power, power factor (FP), peak demand current, energy losses and voltage drop, considering impacts of reliability, maintenance, energy consumption costs and penalties, showing a new way of address energy efficiency issues aligned with maintenance and asset management.

Energy efficiency, Maintenance, Asset management

Resumen

Actualmente, el desarrollo de sistemas eléctricos implica abordar tópicos de rentabilidad en sus procesos, donde la toma de decisiones orientadas a la eficiencia energética sin considerar posibles impactos sobre ciertos riesgos puede presentar altos costos no rentables para una planta. La integración de gestiones de eficiencia energética, de mantenimiento y de activos es importante para las organizaciones. Este trabajo muestra un caso de estudio donde se presenta un problema de compensación de potencia reactiva, mediante el análisis desde un modelo de gestión de mantenimiento alineado a una gestión de activos, se muestra la aplicación de diferentes indicadores técnicos de mantenimiento, confiabilidad y gestión económica relacionados con parámetros eléctricos como lo son; potencia activa, potencia reactiva, potencia aparente, factor de potencia (FP), corriente de la demanda máxima, pérdidas de energía y caída de tensión, considerando impactos de confiabilidad, mantenimiento, costos de consumo de energía y penalizaciones, mostrando una nueva forma de abordar problemas de eficiencia energética alineados con el mantenimiento y gestión de activos.

Eficiencia energética, Mantenimiento, Gestión de activos

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Introduction

The changes that are occurring in the electrical grids demand management strategies that allow an optimization of critical assets at the generation, distribution, transmission, and sub-transmission levels, resulting in better profitability, risk control, operational reliability, energy saving and efficiency [1,2,3].

Electric energy efficiency is an important topic area where strategies have been implemented where many times it fails to consolidate, because it has been focused mainly on effectiveness (short-term actions) and not on efficiency (medium and long-term actions) and evaluation, having an emphasis many times on billing costs without considering the impacts that can occur in the maintenance, reliability and profitability of a plant [4,5]. On the other hand, it is very common to observe the need to have an asset management model that considers aspects of energy saving and efficiency, maintenance, reliability and profitability in industrial plants in an aligned way, otherwise undesirable situations may arise. In Fig. 1. it can be seen that there must be a hierarchical level, where the Asset Management is the most important level to consider in an industrial plant.

This work shows a way to address problems related to low effectiveness in reactive power compensation, presenting a new way of considering this type of problem and proposing justified solutions through the use of technical-economic indicators that provide benefits and consider aspects such as they are; energy saving and efficiency, maintenance, reliability and profitability.

In a such sense, section II begins by showing an 8-phases maintenance management model applied to electrical systems, briefly explaining each phase of the model, where phases 1,2,3 and 7 show the analysis of the impacts of a low power factor, which involve savings in billing costs, energy efficiency, maintenance and reliability aligned with asset management.

Section III mentions the concept of asset management, some international standards and shows some of the current problems that electrical systems are adressed.

Section IV shows the conventional methodology for calculating reactive power capacity, showing some calculations of electrical parameters. Section V shows the technical indicators of maintenance, reliability and economic. Section VI shows a case study of a reactive power compensation problem, where considering the calculated electrical parameters and applying the reliability, maintenance and economic indicators, different options can be evaluated.

II Maintenance management model used in electrical systems

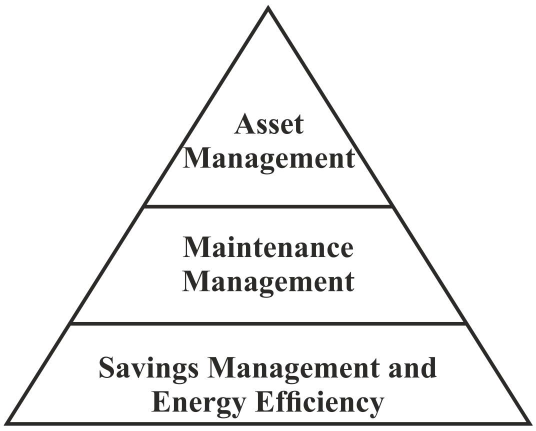

Figure 1 Considerations in energy efficiency management

A consolidated maintenance management model in electrical systems involves the use of tools and methodologies that allow adding value. In Fig. 2, a maintenance management model composed of eight phases is presented [6, 7]. The first three building blocks corresponding to condition maintenance effectiveness, the fourth and fifth ensure maintenance efficiency, blocks six and seven are focused to maintenance and assets life cycle cost assessment, finally block number eight ensures continuous maintenance management improvement. The description of each of the phases is as follows:

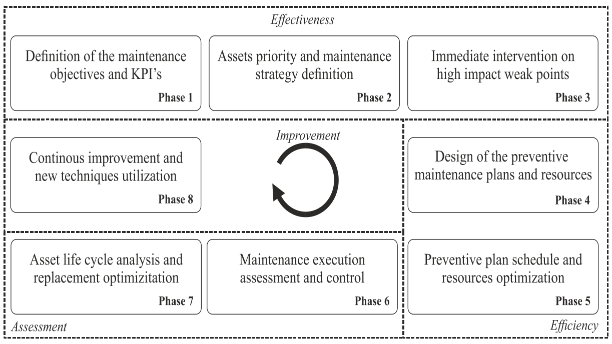

Figure 2 Maintenance Management Model aligned to asset management in electrical systems
Source: [5,6]

Phase 1 shows the objectives set for improvements in a plant, within this stage technical, operational and financial indicators can be found through an information matrix called a balanced scorecard. Phase 2 is related to establishing a criticality in critical systems / equipment / components (such as transformers, tripping of protections that involve a financial loss, etc.). Phase 3 is related to the analysis of significant recurring problems in a plant, where many times due to ignorance of how to deal with them, it is decided to adapt to the problem (such as operating a plant at 70% or otherwise the protections are triggered or adapt to payments for penalties for low power factor and harmonic distortion). Phases 4 and 5 refer to optimizing maintenance plans to avoid the loss of the function of critical assets that could impact the plant (which must be done so that any critical asset continues its function in the operational context). In phase 6, probability distributions are applied considered in the operation of the assets based on basic indicators of maintenance and reliability. Phase 7 refers to the evaluation of assets by projecting all costs throughout the life cycle, considering the impacts in the area of reliability and maintainability of the assets. Phase 8 refers to the use and implementation of new tools that develops improvements in a plant. For the previous model to be profitable in an organization, it must be aligned with asset management as shown in Fig. 1.

III Asset management in electrical systems

Asset management can be defined as the set of activities and practices, systematic and coordinated, that an organization uses to ensure that its assets deliver results and objectives in a consistent, optimal and sustainable manner, managing risk [8]. This definition of asset management represents significantly greater scope considering that energy efficiency and maintenance must be aligned with it.

Currently, electrical systems presents problems, with vulnerabilities and the risk of economic losses due to aging assets, demand growth, limited access to capital for new assets, consequently operating costs are increasing, therefore availability and experience is limited, there is greater pressure from regulators and there is a broad focus on technical management (effectiveness) but management (efficiency) and evaluation must be improved.

Nowadays, some standards have begun to emerge, such as the ISO 55000/01/02 series of guides, which mention recommendations for managing assets throughout the life cycle [10,11,12], where it is recommended to be able to integrate the use of technical indicators with financial indicators.

IV Conventional technical methodology for reactive power compensation solutions

An electrical energy saving and efficiency strategy in a plant is to improve reactive power compensation [13, 14, 15], where the unwanted effects of not compensating reactive power is the increase in the apparent power delivered by transformers and increases in currents in feeders causing a degradation of the operational useful life of the electrical system equipment and high costs of penalties in the energy billing issued by the utility. A technical approach to solve this problem is by measuring electrical parameters such as: active power, reactive power, apparent power, power factor (*PF*), peak demand current, energy losses and voltage drop, and then calculating the required reactive power capacity.

4.1 Calculation of currents

The maximum demand current of the system can be calculated as shown:

$$I_L = \frac{P}{\sqrt{3}(V_{LL})(PF)} \tag{1}$$

Where V_{LL} is the line voltage, P is the maximum demand three-phase power and PF is the measured average power factor. This current of maximum demand, in the billing period, can be given by a measurement directly.

On the other hand, the short circuit current at the point of common coupling (PCC) of the load is:

$$I_{CC} = \frac{S_{CC}}{\sqrt{3}(V_{LL})} \tag{2}$$

Where S_{cc} is the three-phase short-circuit capacity at the load connection point expressed in kVA and is given by the utility.

4.2 Calculation of power factor (PF)

The power factor can be calculated by:

$$PF = \frac{P}{S} \qquad (3)$$

Where P and S are the active and apparent three-phase power, respectively, of a load center, generally given in kW and kVA. A conventional way to calculate PF is by using:

$$PF = \frac{kWh}{\sqrt{kWh^2 + kVArh^2}} \qquad (4)$$

Depending on the measuring instruments, every 5, 10 or 15 minutes during a billing period, or by using the energy consumed in the billing period.

Considering a constant energy demand, the power factor is reduced as the apparent power increases, this due to the increase in reactive power kVAr demanded by the load. By the other hand, reducing the consumption of reactive power delivered by the main transformer will considerably improve the power factor.

4.3 Reactive power compensation using a capacitor bank

To improve the PF, capacitor banks are the most economical solution, whether they can be fixed, automatic connection / disconnection or through a stationary VAr compensator (SVC), depending on the reactive power requirements of a plant. The most conventional is through the use of fixed capacitor banks, where the reactive power calculation (Q in kVAr) to correct the PF is calculated as follows:

$$Q = P(tan\theta_1 - tan\theta_2) \qquad (5)$$

Where:

$$\theta_1 = cos^{-1}(PF_1) \qquad (6)$$

$$\theta_2 = cos^{-1}(PF_2) \qquad (7)$$

Sub-index 1 indicates the actual PF in the system and sub-index 2 indicates the desired PF of the system.

4.4 Penalty and bonus for PF

To calculate an annual penalty for low power factor (APLPF), the equation used by the electricity company in México for high-consumption users is considered. This penalty is applied for power factors less than 0.90, and is given by [3]:

$$\boldsymbol{APLPF = Bill\left(\frac{3}{5}\right)\left(\frac{0.9}{FP} - 1\right)(12)} \qquad (8)$$

Similarly, the APLPF can be converted into a bonus. The calculation for the annual bonus of the power factor (ABPF) is given by:

$$\mathrm{ABPF} = -\mathrm{Bill}\left(\frac{1}{4}\right)\left(1 - \frac{0.9}{\mathrm{FP}}\right)(12) \qquad (9)$$

It is mentioned that the billing showed in this section comes from the sum of a fixed charge for the operation of the basic service provider, the cost of energy consumption and a cost of 2% of use in low voltage (LV).

V Reliability, maintenance and economic management indicators

The objective of management indicators in maintenance is diverse, however in this work some easily applicable indicators that can be related to economic indicators and an adequate profitability through an annual cost projection are shown. Developing maintenance management in a plant, consists of reducing the probability of the presence of faults (reliability), quickly and efficiently recovering the operability of the systems (maintainability) once the interruption of the function has occurred, minimizing the impact due to the consequences of fault events (unavailability costs). Efficient maintenance management seeks to: improve operational continuity (availability), maximize profitability through assets (economic gains) and minimize risks to safety, environment and operations to tolerable levels (consequences of fault events) throughout the useful life cycle [3, 16, 17, 18, 19].

5.1 Technical indicators of reliability and maintenance

The average time of operation (MTTF) is an indicator that shows the operational reliability through an average of the operating times of a component, machine or system.

$$\mathrm{MTTF} = \frac{\sum_{i=1}^{i=n} \mathrm{TTF_i}}{n} \tag{10}$$

Where TTF is the operating time until failure or scheduled is replacement and n is the total number of faults or scheduled replacements in the evaluated period. By means of this indicator, the frequency of failures ff is given by the equation that is inversely proportional:

$$\mathrm{ff} = \frac{1}{\mathrm{MTTF}} \tag{11}$$

This indicator is used in the case of study exclusively in the transformer and in the proposed capacitor banks.

The average repair time MDTTR shows the maintainability of a component, machine or system, as shown:

$$\mathrm{MDTTR} = \frac{\sum_{i=1}^{n} \mathrm{DTTR_i}}{n} \tag{12}$$

Where the DTTR is the down time to repair.

Time out of service (TOS) is an indicator that shows the impacts of time to repair (MDTTR) and time out of control (TOC):

$$\mathrm{TOS} = \mathrm{TOC} + \mathrm{MDTTR} \tag{13}$$

For each TOSi, the time out of control (logistics, unforeseen events, etc.) plus the average repair times are considered, as shown:

$$\mathrm{TOS_i} = \mathrm{TOC_i} + \mathrm{MDTTR_i} \tag{14}$$

Another indicator used is the operational availability (Ao), which can be of various types, for this study the generic operational availability (Ao) of the system for a given period will be considered.

$$\mathrm{Ao} = \left(\frac{\mathrm{MTTF}}{\mathrm{MTTF+MDTTR}}\right) 100\% \tag{15}$$

5.2 Cost of unavailability in reliability (CUR)

It is an economic cost indicator that links the technical indicators ff (fault / year) and TOS (hr / fault) showing the impacts of reliability and maintainability in an annualized monetary value [3,20]. Consider the penalties costs PC (direct costs, penalty, quality, safety, etc) as shown:

$$\mathrm{CUR} = (\mathrm{ff})(\mathrm{TOS})(\mathrm{PC}) \tag{16}$$

5.3 Annualized Total Risk (ATR) for the life cycle

It is an economic indicator that projects annual costs and serves to make a cost comparison of components / equipment / system and is given by:

$$\mathrm{ATR} = \mathrm{AC} + \mathrm{OC} + \mathrm{MMC} + \mathrm{PMC} + \mathrm{CUR} \tag{17}$$

Where AC are the acquisition costs, OC are the operating costs, they include the costs for energy, supplies and raw materials, MMC are the major maintenance costs, PMC are the preventive maintenance costs and the CUR are the costs of unavailability in reliability.

5.4 EBITDA (Earning Before Interest Taxes Depreciation Amortization)

It is a financial indicator that shows the profitability before interest, taxes and depreciation [19,20]. One way to calculate it is given by:

$$\mathrm{EBITDA} = \mathrm{NI} - \mathrm{AMC} - \mathrm{OC} - \mathrm{AE} - \mathrm{SE} + \mathrm{DA} \tag{18}$$

Where NI is the net income (product sold), calculated as:

$$\mathrm{NI} = (\mathrm{PI})\ (\mathrm{Ao}) \tag{19}$$

Where PI is the potencial income ($) and Ao is the operational availability (%).

AMC are anual maintence costs, where preventive, major and corrective maintenance are considered (CUR).

$$\mathrm{AMC} = \mathrm{PMC} + \mathrm{MMC} + \mathrm{CUR} \tag{20}$$

OC are the operating costs. For the present study, only energy consumption expenses are considered, involving the costs of penalties and bonuses for PF.

AE is administrative expenses, SE is selling expenses and DA is depreciation / amortization.

VI Case study. Optimized reactive power compensation

The study presented corresponds to an electrical system of an industrial plant in steady state, there is a 500 kVA transformer, operating at PF of 0.7 (-), which feeds a load of 360 kW. The load is fed by a feeder of 2 conductors per phase 600 KCM size with a length of 100 m, operating 20 hours a day [15]. The Fig. 3 shows the diagram of the current system and the proposed system with its capacitor bank with the aim to guarantee a power factor of 0.95 and avoid any penalties.

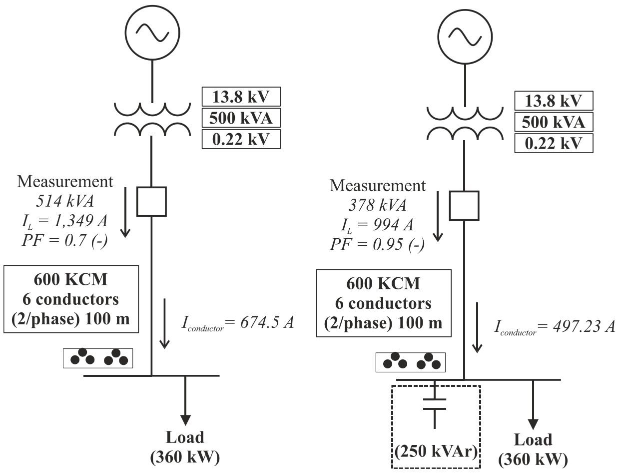

Figure 3 Current system and technically proposed system

For the system in Fig. 3, there is an Ordinary Medium Voltage Large Demand rate (OMVLD). Table I shows the values in the monthly billing, before of compensation this table shows a penalty for low power factor that corresponds to the system without reactive compensation.

Concept	Amount	Charge
kWh	210,000	
kVArh	214,254	
PF	0.7	$118,349.8
kW max	360	
$/kWh	$2.85	$598,588.2
$/kW 2% LV	$85.00	$30,600
$/kW Charge	$170.00	$61,200
TOTAL		**$808,738.75**

Table 1 Initial system billing

If it is calculated the capacitor bank for a PF of 0.95 applying (5) we have:

$$Q = 360(\tan(45°) - \tan(15°)) = 250 \text{ kVAr}$$

By means of this technical solution, it is observed in Fig. 3 that the transformer is not overloaded, likewise the current per phase I_L in the feeders is reduced and consequently the currents of the conductors $I_{conductors}$, this is due to the insertion of the capacitor bank with a capacity of 250 kVAr. The 600 KCM size conductor has a resistance of 0.0753 Ω / km, therefore the resistance for a distance of 100 m is:

$$R = 0.1(0.0753) = 0.00753\ \Omega$$

Where the losses considering the current in the conductor for the uncompensated system is:

$$P = 674.5^2(0.00753) = 3.425 \text{ kW}$$

And for the system with compensation:

$$P = 497.23^2(0.00753) = 1.861 \text{ kW}$$

It can be observed the low reduction of losses, for the compensated system the billing values are shown in Table 2, it is observed a bonus for power factor.

Concept	Amount	Charge
kWh	204,389	
kVArh	69,034	
PF	0.95	-$8,437.28
kW max	360	
$/kWh	$2.85	$582,454.5
$/kW 2% LV	$85.00	$30,600
$/kW Charge	$170.00	$61,200
TOTAL		**$665,871.07**

Table 2 System billing with compensation

Comparing Tables I and II, is shown a clear reduction in the monthly cost. On the other hand, there is a reduction in monthly energy consumption due to losses in the cables of:

$$P_{saving} = (3.425 \text{ kW} - 1.861 \text{ kW})(6 \text{ conductors})$$

$$(20 \text{ hr/day})(30 \text{ day}) = 5{,}630.4 \text{ kWh}$$

Which represents a saving of $ 16,046.64 considering the cost per kWh of $ 2.85.

For the return on investment of the capacitor bank, a cost of $ 250,000.00 is considered, then the simple return on investment is given by:

$$\mathrm{ROI} = \frac{\$_{\text{solution}}}{\$_{\text{Annual saving}}} \qquad (21)$$

Where the return on investment is approximately in two months:

$$\mathrm{ROI} = \frac{\$250{,}000.00}{(\$808{,}738.75 - \$665{,}871.07)} = 1.74 \text{ months}$$

It is worth mentioning that this technical solution proposal through the ROI indicator does not consider the impacts of reliability and maintenance.

Using the model shown in Fig. 2 and through the first three phases, it is possible to analyze a recurring problem that corresponds to a low PF.

Phase 1 corresponds to the objectives set by management, which are set out in a balanced scorecard, where technical and economic indicators are considered, as shown in Table 3.
Phase 2 corresponds to determining the equipment and systems that are critical in a plant, in a such sense in Table IV it can be observed the technical problems that impact management objectives.

Strategic objetives	Measures (KPI's)	Goals	Action	Perspective
Improve profitability considering the maintenance, reliability and efficiency and saving of electrical energy in the plant	Power Factor (*PF*), Electric Power Billing Costs in impacts on reliability and maintenance (*CUR*), Annualized Total Risk Indicator (*ATR*) *EBITDA* financial indicator	Increase profitability Improve maintenance, Improve reliability Improve energy savings and efficiency Decrease in operating costs (electrical energy)	Ensure adequate data acquisition (Billing costs, Evaluation of Cost-Risk-Benefit solutions) Simulations with software to avoid unwanted events (resonances) Development of new internal policies (acquisition, reengineering)	Financial Customers Internal processes Learning and growth

Table 3 Balanced scorecard, showing technical and financial indicators

Technical-operational problems		Costs to mitigate
Low PF of 0.70	Impacts on	Costs of penalties in energy billing and non-compliance with regulations
Transformer with overload (103%)	Impacts on	Corrective maintenance costs and penalties
Feeders with improper currents	Impacts on	Corrective maintenance costs and penalties

Table 4 Unwanted situations associated with a deficiency in reactive power compensation

Phase 3 corresponds to the analysis of vulnerabilities, which corresponds to unwanted events present in critical equipment / systems. The unwanted event of a low PF is a recurring problem that impacts management objectives, which corresponds to an analysis of the technical solution (250 kVAr capacitor bank).

Key Performance Indicators	Transformer
MTTFTranf (years)	20
ffTranf (Failure/year)	0.05
MDTTRTranf (hour/failure)	72
TOSTranf (hour/failure)	72
PCTranf ($/hour)	5,000.00
MCTranf ($/year)	24,000.00
ACTranf ($)	750,000.

Table 5 Technical maintenance and reliability data of capacitor banks

Considering the impacts of reliability, maintainability and profitability, the equations shown above are applied using data collected in the plant. Table V shows the transformer data, where the cost per penalty corresponds to lost in production due to total interruption.

Annualized Major and Preventive Maintenance Costs are in $CM_{Tranf.}$ For this case, it is mentioned that only a single transformer fault mode is analyzed in the three conditions.

Key Performance Indicators	Capacitor Bank Type 1	Capacitor Bank Type 2
MTTFCap (years)	4	1
ffCap (Failure/year)	0.25	1
MDTTRCap (hour/failure)	24	24
TOSCap (hour/failure))	24	24
PCCap ($/hour)	164.37	164.37
MCCap ($/year)	3,000.00	3,000.00
ACCap ($)	250,000	150,000

Table 6 Maintenance and reliability technical data of transformers

Table VI shows the data of the two types of capacitor banks proposed from different utilities, where the technical characteristics of each of them are observed. It is mentioned that the PC_{Cap} penalty costs are calculated based on the billing when there is a penalty for low FP, considering the capacitor bank in fault, either type 1 or type 2. The difference in the types of capacitor banks is according to the technical characteristics of maintenance, reliability and investment costs shown in Table 6.

Annualized major and preventive maintenance costs are in CM_{Cap}. For this case it is mentioned that only a single fault mode of the capacitor bank is analyzed.

With the above data, indicators are calculated that allow selecting the most appropriate proposal as shown in Table VII.

PF	0.7	0.95	0.95
Total CUR ($/year)	36,000.00	37,972.50	43,889.99
ATR ($/year)	9,802,364.95	8,155,425.31	8,248,842.80
TMC ($/year)	60,000.00	64,972.50	70,889.99
OC ($/year)	9,704,864.95	7,990,452.82	7,990,452.82
Ao	0.9992	0.9991	0.9990
PI ($/year)	10,000,000.00	10,000,000.00	10,000,000.00
NI ($/year)	9,991,787.57	9,990,875.91	9,989,573.83
AE($/year)	20,000.00	20,000.00	20,000.00
SE($/year)	30,000.00	30,000.00	30,000.00
DA($/year)	300,000.00	300,000.00	300,000.00
EBITDA($/año)	476,922.62	2,2185,450.60	2,178,231.03

Table 7 Scenario evaluation using technical and financial indicators

In the study of the CUR indicator for each scenario, in the initial condition it is only applied to the transformer and in the subsequent conditions it is applied to the transformer and capacitor bank, showing that the initial condition is the most favorable, however this indicator is limited only to consider corrective maintenance costs, reliability and penalties. The best practice of application of this indicator should be to compare similar systems, in the study is observed that the system with the type 1 capacitor bank is more convenient than the system with the type 2 capacitor bank.

In the study of the ATR indicator for each scenario, the investment costs of each component of the system are considered. The operating costs involve the annual energy billing with a penalty and bonus for PF. For the costs of preventive maintenance (PMC), major maintenance (MMC) and corrective maintenance (CUR) there is an annualized value of $ 60,000.00 for the initial condition, of $ 64,962.50 for condition with the capacitor bank type 1 and of $ 70,889.99 for the condition with capacitor bank type 2. In this analysis it is observed that although the investment costs are higher for the condition with the capacitor bank type 1, the lowest costs projected annually are obtained, being the most favorable condition.

For the interpretation of the EBITDA indicator, which is a financial indicator of profitability, emphasis is placed on the variables NI, TMC and OC, where in the NI indicator the impact produced by availability Ao is observed, which in turn is linked to the indicators MTTF and MDTTR. The TMC variable shows how the CUR indicator that links the ff, TOS and PC influences. Finally, in the OC, it is observed how reactive compensation influences the billing of electricity consumption, with penalties or bonuses. The PI and the costs of AE, SE and DA are considered fixed costs. In this analysis, the most favorable condition is the system with the capacitor bank type 1, having the highest annual projected monetary value.

VII Conclusions

The problem of improving the power factor in an industrial plant is very common, mainly in installations with several industrial loads, where selecting a technical solution for reactive power compensation problems requires considering additional factors such as maintenance, reliability and financial indicators. In this work, indicators allow to justify criteria that improve the profitability of a plant considering aspects of reliability, maintenance, energy saving and financial. Through a maintenance management model that considers energy savings and efficiency aligned with asset management, it is possible to analyze recurring problems through the proposed phases 1, 2, 3 and 7, that considering the most appropriate condition for the plant.

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