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Article

Power Shunt Capacitor Bank Management Model Based on Life Expectancy and Risk Overtime

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Abstract: In this paper is presented a model to assess shunt power capacitor banks. The model seeks to support decision making by optimizing incomes and considering risk. Hence, to model incomes the revenue, maintenance cost, electrical losses, dismantling cost and risk are considered. The risk is monetized as a critical cost times probability of failure. Probability of failure is estimated using shunt bank degradation. To assess the model, the data of an operating shunt bank was used and the Colombian regulation was assumed for financial values. As a result, different maintenance strategies was evaluated in order to know the optimum one.

1. Introduction

Shunt power capacitor banks (SB) are widely used in power systems to compensate reactive energy produced by inductive loads. These banks can be also used as filters using series reactors for reducing harmonic content of the grids. Even for both applications can be used at the same time. Hence, under operation, shunt banks are stressed to voltage and currents. In consequence, capacitor's life cycle depends on over-peaks caused by voltage and current distortion.

Improper management of shunt capacitors might considerably reduce their life expectancy and therefore their reliability, increasing risk during operation. To assess capacitor banks life expectancy, experiments realized on metallized polypropylene film capacitors (MPPF) in addition with statistical analysis are addressed in [1, 2, 3], where empirical models to estimate the lifetime of these kind of capacitors were developed. These models are based on characteristics of voltage wave in order to estimate lifetime by assessment the degradation of capacitance and $\tan(\delta)$.

To improve the shunt banks management, asset management emerge as tool to support decision making considering cost, risk and performance. To illustrate, In Colombia by CREG's 015 of 2018 resolution [4] is enforce to utilities to certificate in asset management system according to the standard ISO 50001 [5]. This in order to optimize asset's investment and maintenance by using techno-economic models.

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In this work is proposed a model to assess shunt banks in an asset management framework considering cost risk and performance. With the proposed model, power shunt capacitor bank lifetime whose function is filtering harmonics and compensate reactive energy can be assessed. However, Capacitor bank units use oil as dielectric (different from MPPF of the experiment) is assumed, hence it is expected to results be an approximation. In order to estimate the risk, a probabilistic model to determinate SB reliability based on health index and failure rate is presented. This model address a financial management of capacitor banks seeking estimated when investment on maintenance is optimum. Finally, the model is evaluated with a 115 kV - 45 MVAr shunt bank estimating its expected life, risk and maintenance frequency.

2. Background

In this section is addressed the estimation of SB elapsed life using the health index (HI).

2.1. SB Health Index - HI

Health index is a measure of the current state of asset. HI value can normalized between zero and one, where, zero represents the best possible condition and one, the worst possible. This index can be expressed by (1) [6],

$$HI = HI_0 \cdot e^{A_f(T_2 - T_1)}, \tag{1}$$

where HI_0 represents the initial index (commonly is taken as 0.01), T_1 is the initial year, T_2 is the year of study and A_f is an aging factor. A_f depends on SB initial life expectancy.

Despite of (1) is used commonly to estimate HI during time, it has problem in life cycle management model because a health index greater than is one can be possible. In consequence, a Weibull distribution can be used in order to improve asset's lifetime model and avoid HI greater than one [7]. The Weibull distribution probability is given by (2),

$$HI = 1 - e^{-(\frac{\Delta t}{\lambda})^k}, \tag{2}$$

where λ and k are known as shape and scale parameter, respectively. According to IEEE standard 1036 [8], "Life to 90% survival might exceed 20 years when capacitors are applied according to the guidelines of this application guide". Using this point as reference and fitted λ and k the 1 can be described by (2).

As shunt capacitor bank is made of a combination of series and parallel capacitors, in this paper is proposed to assess each cell in order to improve the SB assessment. In this way, the maintenance influence on the SB HI depending of how many cell are changed at a given time. Hence, a compound health index is defined by (3),

$$HI_c(T) = \frac{HI_T \cdot [NC - \sum_{t=1}^{T} Re_t] + \sum_{t=1}^{T} HI_{T+t-1} \cdot Re_t}{NC}, \tag{3}$$

where HI_T corresponds to health index determined by (2) at time T, NC is the number of capacitors and Re_t is the number of cells replaced at given time t.

2.2. SB Reliability

With the health index is possible estimate SB reliability in order to asset the risk by using the probability of failure and the impact of the failure.

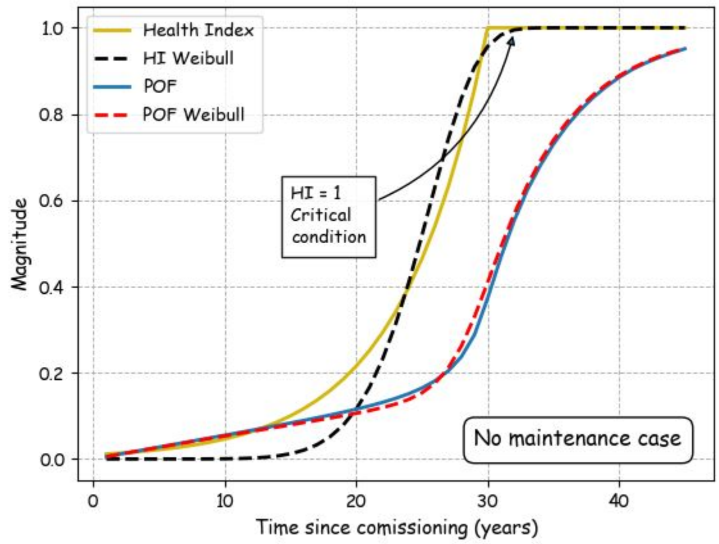


Figure 1. Both Health Index and Failure Probability comparison using 1 and Weibull fit 2

2.2.1. Failure Rate

In [9] is proposed the equation (4) to estimate the rate of failure (λ) of an asset by using its HI,

$$\lambda(HI) = Ae^{B \cdot HI} + C, \tag{4}$$

For shunt capacitor banks, in [9] are proposed the constants A=0.00155, B=4.67297, C=0.00394. However, these values need to be fitted using historical records of failures.

2.2.2. Reliability and Probability of Failure

Reliability is one of the most important issues to support decision making. A high reliability allows an management reducing asset risk. The reliability (R) during time can be estimated with the failure rate using (5),

$$R(t) = e^{-\int_0^t \lambda(t)dt}, \tag{5}$$

Finally, probability of failure can be computed by 6.

$$POF(t) = 1 - R(t), \tag{6}$$

In Figure 1 is shown the HI computed by using both equations (1) and (2) which parameters were fitted. The POF for both HI was calculated obtaining a similar behavior.

2.3. Residual Life

For a long-term asset management, some models are used to predict shunt banks lifetime based on temperature, overvoltages, partial discharges, moisture and humidity [10]. In this paper, the model to estimate lifetime deterioration of SB uses voltage distortion.

According to [1], by using (7) SB residual life based on parameters associated with voltage can be estimated,

$$\ln L = 15.9 - 0.81 \ln\left(K_f\right) - 5.33 \ln\left(K_p\right) - 1.96 \ln\left(K_{rms}\right), \tag{7}$$

where K_f, K_p and K_{rms} and factors that describe the voltage waveform, and their are calculated following [1, 2]. Applying an exponential to (7) on both sides of the equation and adding some terms, the resultant formula for estimating elapsed life is,

$$L = \frac{L_0 \cdot K_u}{K_f^{0.81} \cdot K_p^{5.33} \cdot K_{rms}^{1.96}}, \tag{8}$$

where L and L_0 are the SB residual life and rated SB life expectancy, respectively. Rated life expectancy K_u is defined by manufacturer, otherwise this can be assumed as 20 years.

2.3.1. Overpeak factor K_p

This factor is defined as the relationship between rate peak voltage V_p^{rate} and the operating peak voltage V_p^{opt} as is shown in (9). It is considered as the factor with the higher influence,

$$K_p = 1.16 \cdot \frac{V_p^{opt}}{V_p^{rate}}, \tag{9}$$

It is noticeable that experiments [1, 2] that supports this equation were made on low voltage capacitors. Therefore, there is a constant of 1.16 that multiply the factors in order to extrapolate those results into high voltage. According to IEEE 1036 [8], "Capacitors are suitable for continuous operation at 135% of rated reactive power". This means that shunt banks must be rated at 116% of system operation voltage.

2.3.2. Harmonic distortion factor K_f

As shunt capacitor banks can be used for filtering harmonics, harmonic content also influence the SB degradation. This effect can be describe by the factor K_f describe by 10,

$$K_f = \frac{\omega_1}{\omega_0} \sqrt{\sum_{h=1}^{N} h^2 a_h}, \tag{10}$$

where ω_0 is the rated angular frequency, ω_1 is the fundamental angular frequency of the voltage waveform, h is the ratio between ω (harmonic order) and ω_1, and $a_h = \frac{V_h}{V_1}$.

2.3.3. RMS Factor - K_{rms}

this factor is defined as the ratio between the rate RMS voltage wave V_{rms}^{rated} and RMS value of voltage wave during operation V_{rms}^{opt}, given by (11),

$$K_p = 1.16 \cdot \frac{V_{rms}^{opt}}{V_{rms}^{rate}}. \tag{11}$$

2.3.4. Use factor - K_u

This factor is related to shunt capacitor work hours. K_u is defined as the inverse of fraction of hours per month that shunt bank is operative.

2.4. Elapsed Life - Experimental Alternative

In order to explore another alternative to calculate the residual life previously described, in equation (12) is described an empirical formula [3],

$$101119,3C = L + 3321,31T + 420,0539, \tag{12}$$

Where C is the ratio between the current capacitance and the original capacitance and T is the ratio between the current and original $tan(\delta)$. This formula can come in handy where there is a periodic measurement of the capacitance. However, if there is no data available, one can extrapolate the results from [3] by applying an exponential regression and obtaining an alternative formula (13) that depends only on the life expectancy K_u and the main factor K_p,

$$L = (2,73 \cdot 10^7) \cdot (2,94 \cdot 10^{-3})^{K_p} \cdot Ku. \tag{13}$$

3. Techno-Economic Assessment

In this section is addressed the proposed techno economic model to estimate optimal SB maintenance.

In order to enhance SB management is necessary to estimate the time when maintenance is optimum. To estimate these time is required to asses financial incoming and out-coming during operation of the SB. In this paper is proposed the equation (14) , which is based on revenue model proposed by Colombian regulation, CREG 015 [4]. This resolution establish the methodology to remunerate operation of different assets including shunt power capacitors banks,

$$\begin{aligned} Prof = \int_0^T Ren\,(t) \cdot dt - \int_0^T RI\,(t) \cdot dt + \int_0^T Mai\,(t) \cdot dt - \\ \int_0^T Loss\,(t) \cdot dt - Dis_{t_{end}} - \int_0^T Inv\,(t) \cdot dt, \end{aligned} \tag{14}$$

where $Prof$ is the total profit for operating the SB, Ren is the SB revenue according to CREG, R is the financial risk, Mai is the maintenance revenue according to CREG resolution, $Loss$ is the cost by power losses on SB, Dim are the dismantling cost and finally Inv is the utility capital investment and associated maintenance cost.

The optimization problem consists in to estimate the maintenance times in which the profit is maximum as is shown by (15). In this paper, these times are estimated using combinatorial optimization varying inversion, maintenance time and risk in order to get the maximum profits,

$$\begin{aligned} \max_{t_1,t_2,\ldots,t_n} \quad & \mathrm{Prof}\,(t) \\ \text{subject to.} \quad & t_{k-1} < t_k, \\ & t_k > 0 \end{aligned} \tag{15}$$

Cash flow is expected to be positive after incomes lead initial investment, but negative when risk is higher than investments and fines as consequence of SB failure, turning down profits.

3.1. Risk cost - RI

Risk associated to failure of a shunt bank represents financial losses during operation if maintenance is not done. This risk can be estimated using SB POF and its associated a critical cost (Cr). However, the POF growing along time as a consequence of condition degradation and is considered accumulative. In this paper is proposed to associate the C_r as the penalties and reparation costs associated to a SB failure. Hence, the risk is defined by (16),

$$RI\,(t) = POF\,(t) \cdot Cr. \tag{16}$$

3.2. Revenue - Ren

To compute the SB revenue, in this paper is used the CREG resolution [4], where is stated that assets with function of compensating reactive energy will be revenue during 35 years since their start up at an interest rate of 13% acording to (17),

$$Ren\,(t) = RC + (CI - t \cdot RC) \cdot r, \tag{17}$$

where CI is the investment cost or capital investment, RC is CI divided by remuneration time and r the interest rate.

3.3. Investment - Inv

Corresponding to cost that must be done for capacitor's replacement. Assuming that all SB cell are changed during maintenance, the maintenance cost is equal to CI. However, when investments are postponed during operation the net present value decreases as is shown by (18),

$$Inv\,(t) = \frac{CI}{(1+ri)^t}. \tag{18}$$

3.4. Power Losses cost

These cost corresponds to fixed costs during operation of asset's life as a consequence of power losses dissipated by capacitor's ohmic resistance. In most of cases, this losses are less than 0.1 W/kVA. Hence, losses cost commonly are calculated by $/kWh times energy losses per year.

4. Validation

In this section, the proposed model is assessed assuming a 45 MVAr, 115 kV shunt capacitor bank designed according to IEEE 1036 [8] assuming a expected life of 30 years. The assessment is done in two scenarios, the first one assuming non-harmonic content and is the second one considering voltage harmonics distortion.

The Shunt bank's financial parameters according to resolution CREG 015 [4] are shown in table 1. Maintenance revenue according to CREG is 3% of CI . The interest was assumed as 12% and the critical cost was assumed as 200 million pesos (0.3 p.u.) [11]. For the next charts, profits are expressed in per units (p.u.) and the base is the investment cost CI.

	Cost
MVAr	590.8
Installation	73.6
CI	665
r	13%
ri	12%

Table 1. CREG 015's costs. (In million of cops.)

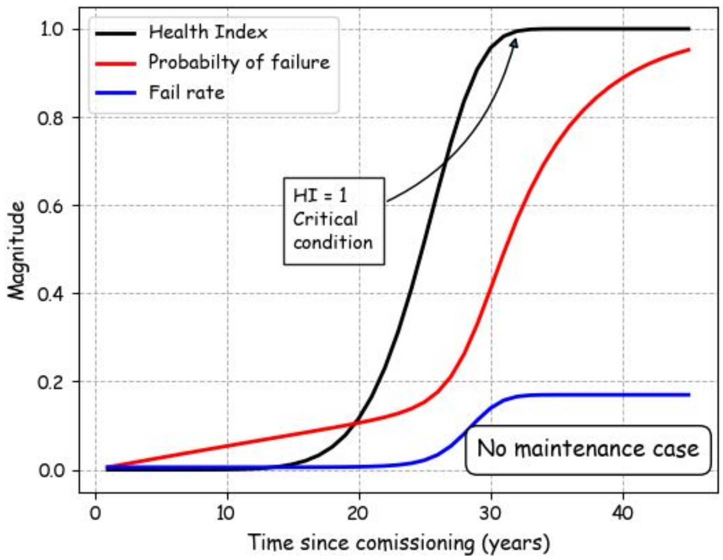


Figure 2. POF, HI and failure rate of the ideal case without maintenance.

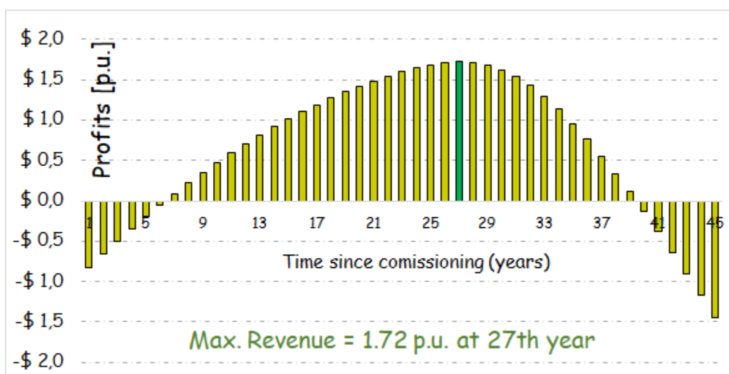


Figure 3. Ideal Cash flow without maintenance.

4.1. Scenario 1: No harmonic content

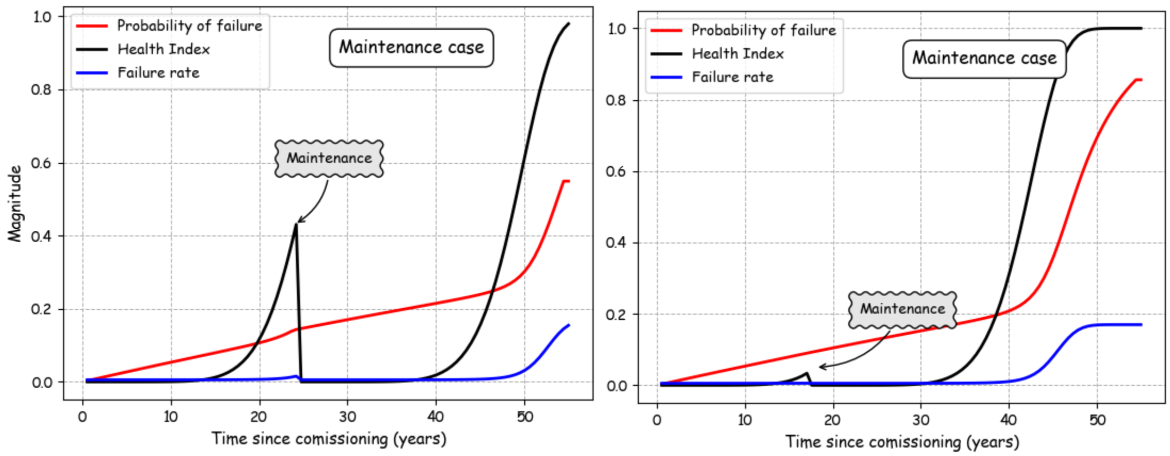
In this scenario is assumed voltage wave without harmonic distortion. Therefore $K_p = 1, K_f = 1, Krms = 1$ and operating all the time.

4.1.1. SB without Maintenance

According to the previous equations and assumptions, the POF during operation is given by (6), which is computed using λ computed with (4) as a function of HI (2). The values of this index are shown in Figure 2. The cash flow for this scenario is shown in Figure 3. Where is observed that maximum profits are achieved in year 27. It is also expected that during the 40th year, the profits become negative because of an excessive amount of penalties accumulated as a consequence of high risks.

4.1.2. SB with Maintenance

Utilities need assessing different scenarios in order to get a optimal decision taking into account cost and risk. To illustrate, in Figure 4 is shown the behavior of HI, λ and POF assuming an strategy with one maintenance in the year 18 and other one in the year 25.



(a) Maintenance at 25th year. **(b)** Maintenance at 18th year.

Figure 4. Maintenance strategy considering different years along useful life of 30 years.

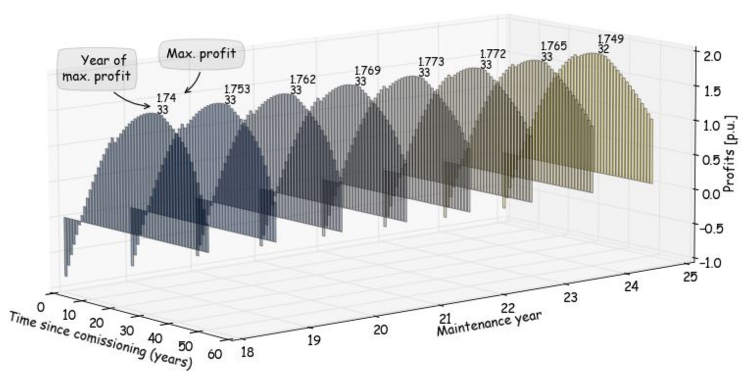


Figure 5. Cash flow for different maintenance strategies assuming one SB maintenance.

According to Figure 4, maintenance at the year 25 can extend shunt bank's life for more than 25 years and in the other case for 15 years more than the original life expectancy of 30 years. In this case, one can notice that there is an optimization problem involved: the useful life increases as the risk gets higher.

Cash flows assuming one maintenance for different times is shown in Figure 5, where can be appreciated that multiple years of maintenance involves different cash flow scenarios. In this case, it can be appreciated that best maintenance strategy would be the one at year 23 because maximum profits are achieved after maintenance.

4.2. Scenario 2: Voltage wave with harmonic distortion

In this scenario, a power SB operating under voltage harmonic distortion is considered. The SB is used for both reactive compensation and 5^{th} harmonics filter. As a consequence of harmonics, life degradation of SB is assessed because of differences between rated and operation voltage. The characteristics of the SB are presented in Table 2.

According to measurements, both the voltage and fundamental waves are shown in Figure 6, where can be observed the difference between these signals. With this harmonic content, lifetime degradation is

Feature	**specifications**
Capacitance	9,02 uf
Order and magnitude of harmonics	5 to 20% V
Operation voltage	125 kV
Design voltage	135 kV
Losses	0,05 W/kVAr
Power	45 MVA
Dielectric	Edisol VI
Useful life	30 years
Use	50% of ay

Table 2. Shunt bank characteristics

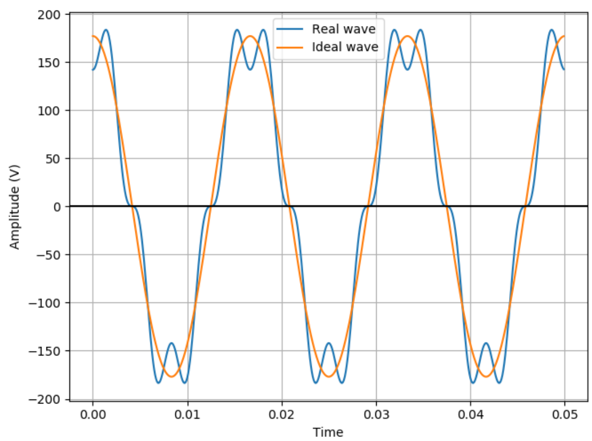


Figure 6. Both fundamental and harmonic wave of voltage.

presented according with [1, 3]. Using (10, 9, 11) $K_{rms} = 1.1$, $K_f = 2.94$ and $K_p = 1.12$. Hence, using (8) the expected life is,

$$L \approx 12 \ years$$

,

According to utility reports, in the year 9 the shunt bank started to fail and during the 11th year the SB was permanently disconnected due to mayor and dangerous failures. This result is in accordance with the real results obtained with the proposed model.

4.2.1. Assessment of SB without maintenance

In this case, it was assumed no maintenance during shunt bank's life expectation. The indexes are shown in Figure 7.

The cash flow for this case in shown in Figure 8. In this scenario can be appreciated that the positive profits margin is lower and failures are expected to be more recurrently in comparison with the scenario 1. Hence, improper management would finish in financial losses. The maximum profit is expected at year 11.

4.2.2. Assessment of SB with maintenance

In this assessment a maintenance strategy is considered. (9) shows the index for maintenance at years eight and eleven. Here can be appreciated the influence of the maintenance on the HI, POF and λ.

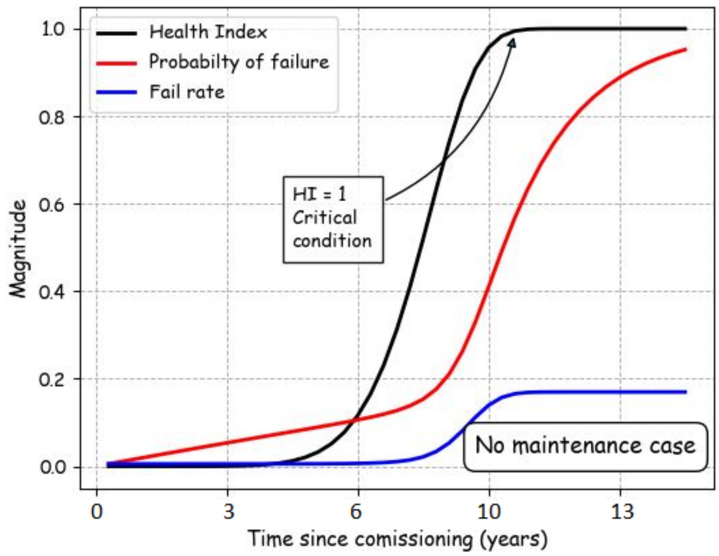


Figure 7. POF, HI and λ for the real case without SB maintenance.

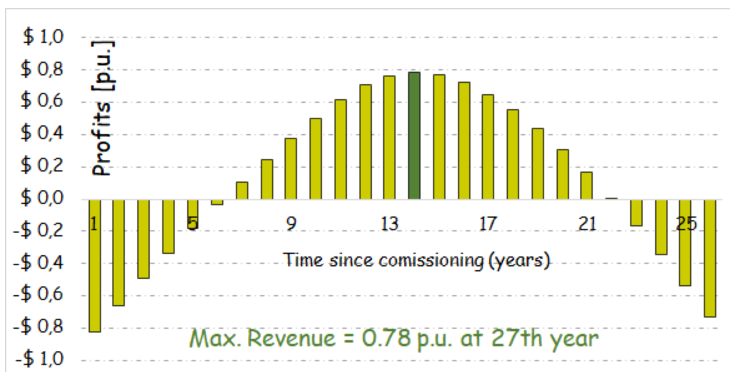
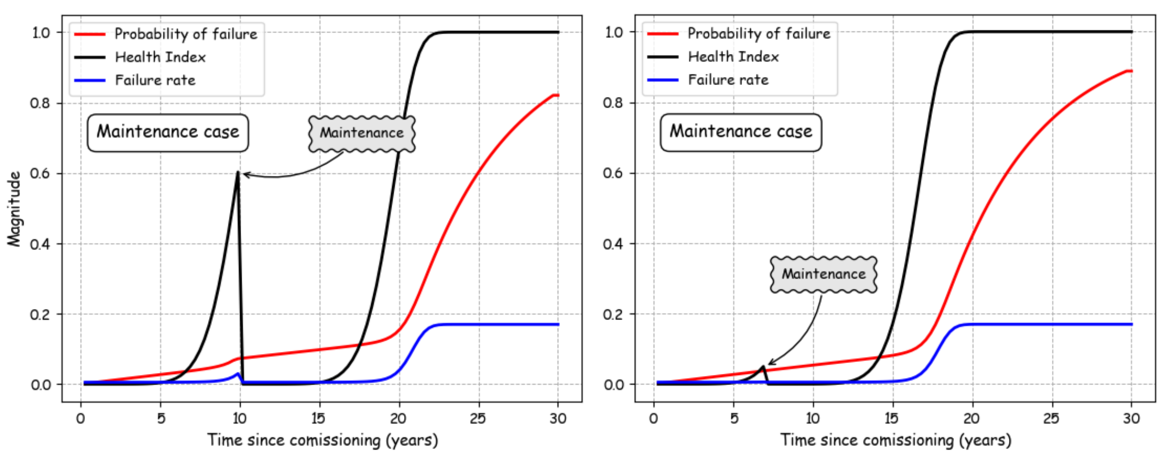


Figure 8. Cash flow of real case without maintenance.



(a) Maintenance at year 11

(b) Maintenance at year 8

Figure 9. SB Maintenance during different years along useful life of twelve years.

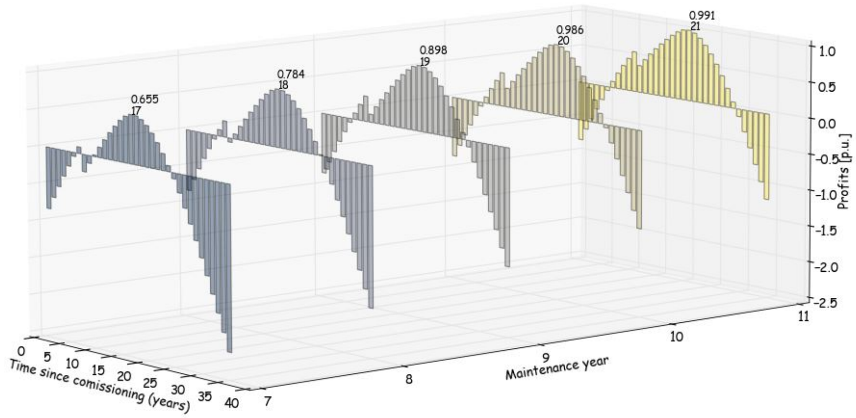


Figure 10. Cash flow for different maintenance strategies.

In Figure 10 is shown the flow cash for different maintenance strategies. According to this plot, a maintenance at year 11 is the optimum one because achieves the highest profits. However, it is necessary to take into consideration that this is the year estimated by the equation (8) where the health index achieves it worst condition.

5. Conclusion

In this document was addressed a model for management shunt capacitor bank. This model is based on estimation of lifetime. With this estimation, health index, failure rate and probability of failure indexes are calculated.

A methodology to assess critical cost was proposed in order to estimate the risk of a shunt bank. The risk was taking as the probability of failure times critical cost. With risk varies during operation, an optimization model was stated seeks to maximize the incomes, where the decision variable is the maintenance time. The proposed model was evaluated using the data of an operating SB, as result the cash flows was obtained for different maintenance strategies. Finally, this model can be used to support decision making.

Acknowledgment

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