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An Algorithm for Estimation of SF_6 Leakage on Power Substation Assets

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Abstract: This paper presents an algorithm that evaluates the current state of an asset fleet containing sulphur hexafluoride (SF_6) and estimates its leakage in future electrical power substation projects. The algorithm uses simple models and easy tools to facilitate decision making for transmission and distribution system operator companies. The algorithm is evaluated using data provided by ENEL-CODENSA. The corresponding results are shown, and the estimation values obtained are compared with leakage records in existing assets which helps to understand the advantages and limitations of the algorithm.

Keywords: sulphur hexafluoride (SF_6); algorithm; estimation model; electrical assets; environment

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1. Introduction

In the last two decades, environmental regulations and protocols signed by a great part of the international community, such as the United Nation's Kyoto [1] and Paris agreements [2], led Distribution System Operators (DSOs) and Transmission System Operators (TSOs) to contribute to reducing their carbon footprint [3]. Some power industry companies have already started to estimate their environmental impact in order to include environmental risk assessment as a strategic objective [4]. A way to mitigate those risks, minimize costs, and maximize performance is to implement an asset management system [5], taking into account that an adequate process to estimate environmental impact is needed.

Sulfur hexafluoride (SF_6) has outstanding dielectric properties, with about 2.5 times the dielectric strength of air under the same conditions. SF_6 has a low dissociation temperature and high dissociation energy, which makes it an excellent arc quenching gas. Those characteristics led switchgear manufacturers to use it to design their equipment [6]. However, according to EU regulations, SF_6 has a global warming potential (GWP) that is 22,800 times greater than that of carbon dioxide (CO_2) [7]. It also has a lifetime in the atmosphere of 3200 years relative to CO_2 [8]. Aware of this environmental impact, The European Union (EU) is reviewing its fluorinated greenhouse gases regulation, which include SF_6, in order to reduce its emissions by two-thirds compared to 2014 levels by 2030 [9]. The EU goal is to be climate-neutral by 2050 [10], which is why the European Network of Transmission System Operators for Electricity (ENTSO-E) is willing to commit to reducing annual SF_6 emissions for the existing fleet below 0.5% of the installed SF_6 in 2019. New equipment will tend to be SF_6 free or have very low GWP by 2050 [11].

According to [12], only 0.1% of human-made global warming in 2006 was related to SF_6 emissions, of which around 10% was due to the electric industry. A study from Réseau de Transport d'Électricité (RTE), the transmission system operator of France, showed that its SF_6 releases reached seven tons in 2008. The calculated valuation was EUR 16.8 million, using a penalty value of EUR 100 per ton of CO_2 [13]. The same company stated that in 2018 its SF_6 emissions were equivalent to 138,400 tons of CO_2, representing 13% of total RTE emissions [14].

Potential sources of SF_6 emissions appear from leakage in SF_6-containing equipment and losses during equipment installation, maintenance, and decommissioning [15]. Studies that estimate SF_6 leakage in electrical equipment can be found in the literature. In [16], surveys are used to gather information about top-up operations in SF_6 circuit breakers, resulting in lower and upper bound weighted-average leak rates. Another work studied the influence of temperature on SF_6 leakage in switchgear, giving a lifetime estimation of the analyzed equipment [17]. In order to support decision-making processes, a mixed approach is necessary using the available information of the current fleet and a proper, yet simple, model to estimate the impact of future projects.

This paper proposes an algorithm to evaluate the current state of power substation assets and to estimate SF_6 leakage on forthcoming projects. Its main objective is to facilitate management of assets and the general decision-making process. On one hand, the algorithm employs existing fleet data in order to produce straightforward charts that summarize the current state of SF_6-containing assets. On the other hand, it allows setting a group of parameters into a simple model for a quick SF_6 leakage projection on future projects.

The structure of this work is composed of three sections. The second section presents the algorithm, including the description of each stage. In the third section, the algorithm is applied to SF_6 assets data from ENEL-CODENSA, a DSO in Colombia. In the fourth section, the estimation results from the proposed algorithm and real data are compared.

2. Stages of the Algorithm

The purpose of the algorithm is to provide an understanding of the current state of the fleet and the SF_6 leakage based on the existing data, as well as an estimation of the leakage of a future potential project, all visualized in a single Microsoft Excel file. The resulting workbook is a flexible tool for the decision-making process.

Figure 1 shows the flowchart of the proposed algorithm. The details of each stage will be illustrated in this section.

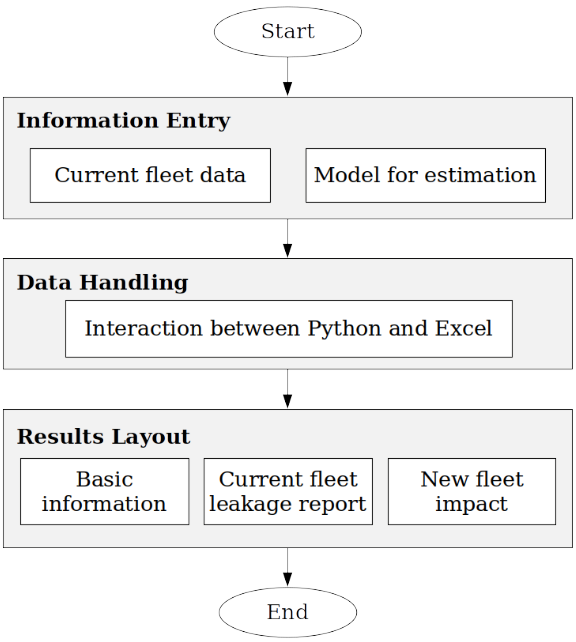

Figure 1. Flowchart of the algorithm.

2.1. Information Entry

The information of the existing assets is provided by the workbook user. This stage of the algorithm is strictly descriptive. The workbook includes a spreadsheet to insert the data. The necessary fields to produce the charts are: substation and module id, year of commissioning, SF_6 initial mass, rate voltage and weight of injected SF_6 mass along with the corresponding dates.

Model for Estimation of SF_6 Leakage

The model selection was defined by the available information sources and the level of complexity. In a first approach, field monitoring measurements on the equipment were taken into account. For this, it was assumed that gas pressure or density measurements would be available for the fleet equipment, so gas behavior models such as one based on density [18], Van der Waals, or Beattie-Bridgeman models could be implemented [6,19]. However, those models assume that changes in density and/or pressure are due only to gas leaks in the equipment and require data that may be difficult to obtain. If such a model could be interesting for realtime monitoring, its consolidation over long-time data makes it appropriate not for a quick estimation of historic leakage but for fast projection for future projects.

A second approach taken into consideration was to use the information provided by the manufacturer about the nominal leakage rate of each asset. Again, very particular and organized information would be required, such as hard to find historical data, which should not be a problem for new projects.

Considering the drawbacks of the first two approaches, a simple linear model was chosen, which depends only on easy to obtain information. Although the flexibility of the model decreases for the sake of simplicity, the parameters of the model can be changed according to the needs of the user, so different scenarios can be easily visualized. The model assumes a constant SF_6 leakage averaged rate per year, which summarizes the combined effect of all assets in all conditions during the lifetime of the project, as observed in previous leakage analyses [6,16,20]. The general model equation is shown below:

$$m_{SF_6} = m_0 \cdot F_p \cdot (t - t_0) \tag{1}$$

where

- m_{SF_6}: leaked SF_6 mass in kg;
- m_0: initial SF_6 mass in the asset in kg;
- F_p: reference leak rate in % kg/year;
- t: year for which the leak is estimated; and
- t_0: year of asset commissioning.

There is an additional parameter named L_{eol}, used to model end-of-life leakages, which considers the emissions related to the handling of the gas for disposal or recycling [21]. This parameter affects only the estimation for the final year t_{end} as shown below:

$$m_{SF_6}(t_{end}) = m_0 \cdot F_p \cdot (t_{end} - t_0) + m_0 \cdot L_{eol}. \tag{2}$$

Additionally, economic impact parameters are used to make an estimation of SF_6 leakage equivalent cost. The model used is presented:

$$m_{CO_2-eq} = m_{SF_6} \cdot GWP_{SF_6} \tag{3}$$

$$CA = m_{CO_2-eq} \cdot CO_{2-cost} \tag{4}$$

where

- m_{CO_2-eq}: mass of equivalent CO_2 in kg;
- GWP_{SF_6}: Global Warming Potential of SF_6;
- CA: cost of environmental impact; and
- CO_{2-cost}: cost of CO_2 emission per ton.

The parameters of time and initial mass of the assets depend on the project to be analyzed. All the values used in equations 1 to 3 can be edited by the workbook user. In the next section the algorithm is used with real data and selected parameter values are further explained.

2.2. Data Handling

Once the data of the current fleet were entered and the parameters of the future project were defined, the corresponding charts were generated. This stage of the algorithm automated the data manipulation using a Python script that processed all the data and produced the charts, which interacts with the Microsoft Excel workbook to present the results in a clear and user-friendly way. The interaction between Python and Excel allows the correct generation of the charts regardless of the number of rows or the range of the data.

2.3. Results Layout

The results of the algorithm are presented in three spreadsheets of the workbook.

2.3.1. Basic Information Sheet

This sheet allows setting the parameters of the estimation model and offers an overview of the current status of assets and their distribution. Data for the current asset fleet are grouped by rate voltage and displayed in a pie chart. A scatter plot is also produced with the distribution of the SF_6 mass in the current assets, grouped by substation and by voltage level.

2.3.2. Current Fleet SF_6 Leakage Report Sheet

This sheet addresses the historical analysis of SF_6 leakage in the current fleet. The leakage is determined as the SF_6 quantity used in a top-up operation. The first two charts plot the mass of SF_6 leakage per year and per substation. The rest of the charts depend on a drop-down list that enables selection of the substation for which leakage by year and by module is plotted.

2.3.3. New Fleet Impact Sheet

With the input of parameters into the basic information sheet and given a SF_6 mass, the new fleet impact sheet presents an estimated impact that includes leakage per year, equivalent CO_2 and annual cost. In addition, a chart plots the accumulated SF_6 leakage in the time span defined with the t_0 and t_{end} parameters. A drop-down list enables changing the visualization between SF_6 leakage kilograms or equivalent CO_2 tons.

3. Results of Algorithm Applied to Real Data

The algorithm was validated using data from the current fleet provided by ENEL-CODENSA, the DSO with the largest coverage in Colombia [22].

In this particular case, the Information Entry stage used the information of 410 SF_6-containing assets. Table 1 shows a portion of the provided assets data and exemplifies the structure of information that is entered in the current fleet data section of this stage.

Table 1. Current fleet data example.

Substation	ID	Year of Comm.	Rate Voltage [kV]	SF_6 Initial Mass [kg]	SF_6 Injected Mass [kg]	Injection Date
VE	2012	2008	115	8	NA	NA
VE	2032	2008	115	8	NA	NA
VE	2042	2006	115	8	NA	NA
VE	2062	2008	115	8	NA	NA
VE	2072	1986	115	4	NA	NA
VE	2082	2008	115	8	0.56	30 August 2012
VE	2092	2008	115	12	NA	NA
VE	2102	2008	115	12	NA	NA

Table 2 shows an example of parameters that can be used in the model for the estimation section of the algorithm's first stage in order to estimate SF_6 leakage. However, users may choose different values according to their needs.

Table 2. Parameters used for the estimation of SF_6 leakage in a new project.

Parameter	Value
m_0	10 kg
F_p	0.5% kg/year
t_{end}	35 years
L_{eol}	10%
GWP_{SF_6}	22,800
CO_{2-cost}	23 EUR/t

The m_0 parameter was arbitrarily picked. The reference leak rate, F_p, is the most important parameter, as it defines completely the rate of growth of the gas leakage in the proposed model; 0.5% is the maximum relative leakage rate per year permitted for SF_6 in closed pressure systems according to IEC 62271-1:2017 standard [23]. The L_{eol} parameter selected is the best guess according to [21].

The GWP_{SF_6} parameter is taken from the European regulation No 517/2014 on fluorinated greenhouse gases [7]. However, a different value may be used based on other sources, as it could actually be 23,500 according to [24]. The cost per ton of CO_2 needs to be adjusted to carbon markets or internal corporate considerations.

According to the Carbon Pricing Dashboard from The World Bank, in order to meet the goals of the Paris Agreement, for the power sector the carbon prices need to be in the range of USD 24–39/tCO_2e by 2020 [25]. EUR 23/t is slightly above that lower bound.

The results of the data handling stage are shown in Table 3, where data is grouped by substation and rate voltage to sum the total SF_6 initial and injected mass values.

Table 3. Data handling stage results example.

Substation	Rate Voltage [kV]	Total SF_6 Initial Mass [kg]	Total SF_6 Injected Mass [kg]
VE	115	68	0.56

The charts generated in stage 2 are shown in Figures 2–5. Note that said charts correspond not only to the partial data shown in previous tables but to the full 410 assets. Figures 2 and 3 show the generated charts with the distribution of SF_6 mass as explained in Section 2.3.1. Figure 4 displays SF_6 leakage per year and per substation. Figure 5 exhibits the result of process described in Section 2.3.3, with the parameter values shown in Table 2. In Figures 2–4, the category labeled as other groups data has lower values to allow the correct visualization of results.

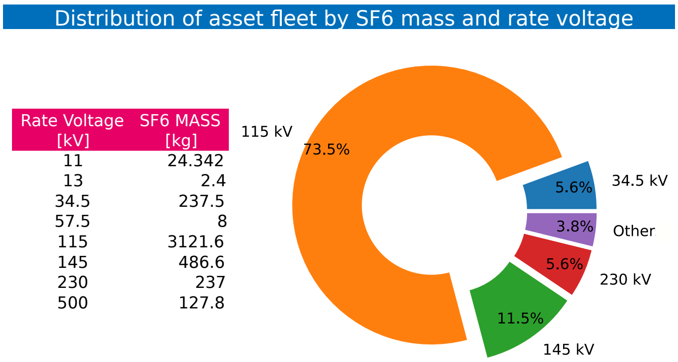

Figure 2. Distribution of SF_6 mass based on ENEL-CODENSA assets data.

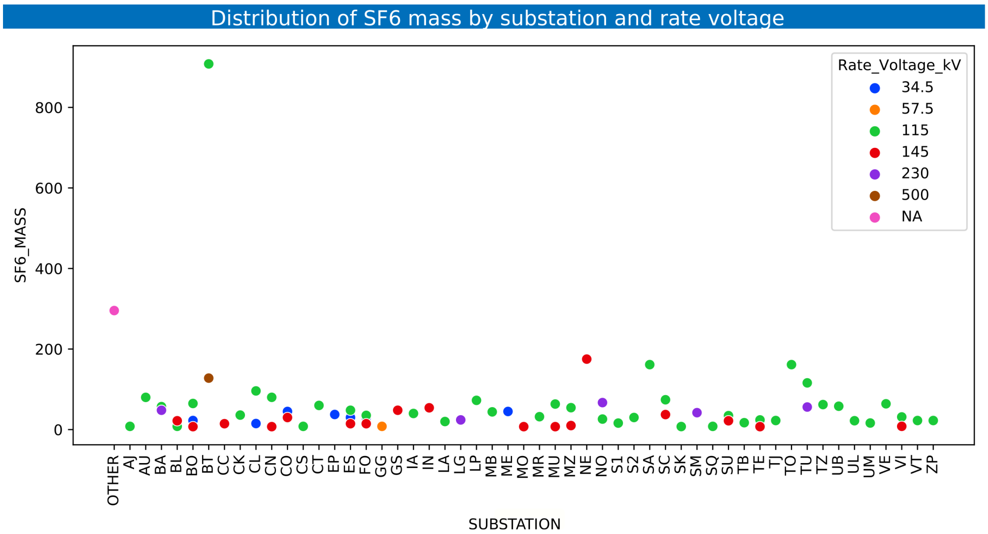

Figure 3. Distribution of SF_6 mass based on ENEL-CODENSA assets data.

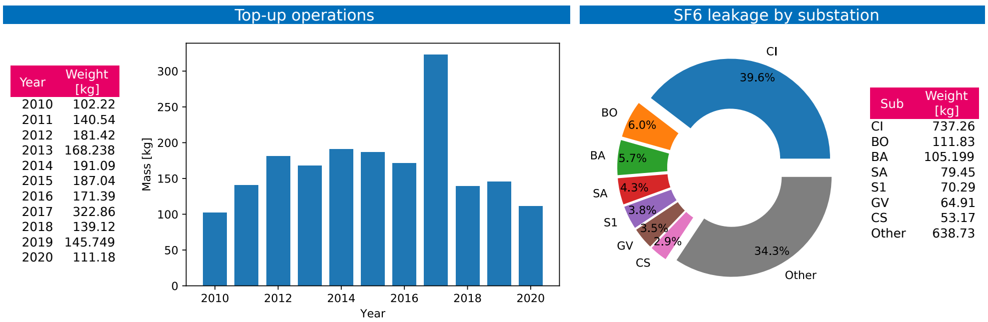

Figure 4. Historical analysis of SF_6 top-ups in ENEL-CODENSA assets.

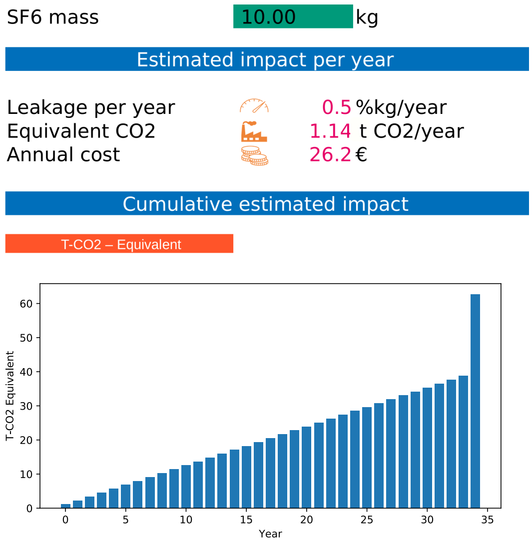

Figure 5. Estimation of SF_6 leakage for a new project according to the parameters given in Table 2.

4. Discussion

The algorithm was designed to achieve simplicity and clarity. However, it was evaluated to understand its limitations and discuss future work. Table 4 compares the results of the linear model estimation, given by Equation (1), applied to data of the current fleet against the available reports of SF_6 leakage, without considering the end-of-life emissions.

Table 4. Comparison of model results against historical data.

Substation	ID	SF_6 Injected [kg]	Model Prediction [kg]	Relative Error %
FO	2082	1.42	0.65	−54.23
UM	2062	0.4	0.18	−55.00
FO	2042	1.05	0.725	−30.95
MU	2012	0.55	0.324	−41.09
AU	2052	0.95	0.6	−36.84
TU	3062	2.06	1.68	−18.45
UM	2032	0.8	0.66	−17.50
VE	2082	0.56	0.2	−64.29
LG	2032	0.7	0.68	−2.86
TZ	2012	0.88	0.8	−9.09
NO	3122	0.8	0.95	18.75
AJ	2012	0.5	0.68	36.00
CO	2042	0.32	0.16	−50.00

Note that a positive error means that the prediction was above the injected mass. That is an indication of better than expected performance regarding gas leakage in the equipment. Negative errors underestimate the leakage. However, reasons for the high error values can be explained and help understand limitations of the algorithm.

Asset 2082 from substation VE, which has the maximum relative error, is a Crompton Greaves SF_6 gas insulated circuit breaker. According to the technical brochure, the equipment has a guaranteed maximum leakage rate of less than 1% per year [26]. The model estimation with a F_p parameter value of 1% is 0.4 kg of leaked gas, with a corresponding relative error of −28.6%. This reduction in the prediction error applies to another 31 assets.

Asset 2082 from substation FO is an ABB HPL145/25C1 circuit breaker installed in 1991, with 0.42 kg of SF_6 injected in 2013 and 1 kg in 2017. This behavior may indicate an inadequate top-up operation in 2013, which led to higher leaks since then. Another influential aspect is the technology available when the circuit breaker was manufactured, as found in [16] where the largest emissions came from the oldest equipment. It is relevant to consider that 142 out of the 410 assets have over 25 years of service.

In addition to the reasons previously mentioned, other factors can be considered to explain high error values:

- Leak rate error: for this specific implementation of the algorithm, an average leak rate of 0.5% was used. However, assets with a longer operating time or lower quality may have higher leak rates, while newer higher building quality assets may suffer less leakage. To solve this problem, as was seen with asset 2082 from substation VE, catalog data could be used instead of average leakage rate.
- Important leaks during the recharging process: the model developed does not take into account leaks that may occur during maintenance of the asset, which can result in a significant mass of gas that is not injected. Manufacturers usually recommend good practices, such as those exposed in [6], for the recharging process to avoid SF_6 leakage.
- Damaged equipment: although the estimation in the algorithm itself is not designed to be compared with historical data, an exaggerated deviation from the model estimation may indicate damages in an asset. Along with the record of top-ups, this kind of result offers the opportunity to anticipate failures and to take proper actions early in order to analyze the situation in more detail and start preventive maintenance.

5. Conclusions

An algorithm for estimation of SF_6 leakage in electrical equipment on power substations was proposed. In the first stage, the information is entered into a Microsoft Excel workbook that includes spreadsheets to fill with current fleet data including top-up records and parameters for leakage estimation of a future project. This well-known tool facilitates the entry of information and the visualization of results. In the second stage, a Python script generates charts by interacting with the workbook. With this, the number of rows, missing records, or range of data do not affect the quality of charts. The final stage of the algorithm presents all the results in three different spreadsheets. Various scenarios can be seen by changing the parameters used to estimate the impact of a new fleet.

In the discussion section it became clear that the algorithm results are not to be compared with historical data, since the objective has a more global approach. When such comparison is made, the explanation of obtained results needs a detailed examination of particular assets. The maximum relative errors found in Table 4 were explained by looking at the characteristics of the assets. However, this comparison presents itself as an opportunity for a better and appropriate selection of parameters.

Atypical values, if any, are clearly identified in generated charts from the results layout stage of the algorithm. This layout makes situations that need special review more evident, such as the CI substation SF_6 leakage observed in Figure 4. This is the way by which the algorithm helps identify strange behavior instead of the comparison of model estimation to historical data.

In this paper, the simple structure of the algorithm and workbook tool was highlighted, as well as its capacity to globally visualize the state of an asset fleet for further decision making and quick estimation of the environmental impact of future projects.

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