Energy Efficiency in Power Transformers

Sorita KALO
Escola Universitària d'Enginyeria Tècnica Industrial de Barcelona
Universitat Politècnica de Catalunya
Barcelona, Spain

Abstract — The objective of this report is to calculate the amount of incentives in order to achieve the potential energy saving of distribution transformers in distribution network.

Firstly, a case study for Spain with the basic data of the power installed of three different energy efficiency rates of transformers has been created. Then the problem formulation in GAMS is presented with the objective function to maximize the benefit in year *n* to fulfill with the demand growth, under the control of the economic constraint RD222/2008 and the improvement overall efficiency constraint.

As a result, the objective of this project can be achieved.

Key words — Energy sustainability, Energy Efficiency, Potential energy saving, Incentive of quality supplies, Incentive of losses reduction

I. INTRODUCTION

Along with the global economic growth, the world energy demands also increase. Because of these reasons, the world has been impacted by the global warming. The R&D of Technologies and the huge amount of subsidies are keys to provide the energy sustainability.

As in the WEO 2012, the renewable energy resources, especially solar and wind energy were predicted to be the most popular resources in 2035 to response with the increase of energy demand in the future and also to replace some conventional energy production technologies[1].

In distribution network, distribution transformers are the second largest loss-making component lines. However, the modern technology can reduce losses by up to 80%. And if we switch the worldwide electricity network to the high efficiency transformer, the potential of energy saving is estimated to be at least 200TWh [2].

This improvement will result the friendly environmental with the low CO_2 emission, no harmfulness for humanity and to reply with to the global energy demand.

According to the SEEDT report, 4.6 million distribution transformers (DTs) are installed in EU-27. This number of distribution transformers are included both less efficient transformer and high efficient transformer; and their losses exceed 33TWh/year [3].

The objective of this project is to provide a calculation method to get the amount of the incentives and the potential energy saving of transformer in distribution network. The case study of this project is for Spain. To achieve this goal, the problem formulation in GAMS [4] program will be formed, under the Economic and the Improvement energy efficiency constraints. And the objective function of the GAMS program is to maximize the benefit to fulfill the growth in demand.

II. TECHNICAL AND ECONOMIC ASPECTS OF TRANSFORMER

1. *Technical Aspects*

A transformer is a four-terminal device that transforms an AC input voltage into a higher or lower AC output voltage. The transformer consists of three main components: the first coil (primary winding) which acts as an input, the second coil (secondary winding) which acts as the output, and the iron core which serves to strengthen the magnetic field generated.

There are many sources of losses lead to temperatures rise which must be controlled by cooling. The primary cooling media for transformers are oil and air [5].

Transformer losses are broadly classified as no-load and load losses. These types of losses are common to all type of transformers, regardless of transformer application or power rating. However, there are two other types of losses: extra losses created by the non-ideal quality of power and cooling losses or auxiliary losses, which may apply particularly to larger transformers, caused by the using of cooling equipment such as fans and pump [6].

No-load loss (also called iron loss or core loss) is present whenever the transformer is energized with its rated voltage at primary winding but the other sets of terminal are open circuited so that no through or load current flows. In this case, full flux is present in the core and only the necessary exciting current flows in the winding. The losses are predominately core losses due to hysteresis and eddy currents produced by the time varying flux in the core steel. It represents a constant, and therefore significant, energy drain. Hysteresis losses: caused by the frictional movement of magnetic domain in the core lamination being magnetized and demagnetize by alternation of the magnetic field. Hysteresis losses can be reduced by material processing such as cold rolling, laser treatment or grain orientation. Eddy current losses: caused by varying magnetic field inducing eddy currents in the lamination. Eddy current losses can be reduced by building the core from thin laminated sheets insulated from each other by a thin varnish layer to reduce eddy currents.

Load loss (or copper loss or short circuit loss): caused by the resistive losses in the windings and leads, and by eddy currents in the structural steelwork and the windings. It varies with the square of the load current. Load losses occur when the output is connected to a load so that current flows through the transformer from input to output terminals. Ohmic heat loss (copper losses): occurs in transformer winding and caused by the resistant of the conductor. The magnitude of this loss increase with I_{load}^2 and $R_{(winding)}$. Ohmic heat loss can be reduced by increasing the cross section of the conductor or reducing the length of conductor ($R=\rho l/s$).Conductor eddy current losses: occur in the windings and caused by alternating current (due to the magnetic field). Conductor eddy current losses can be reduced by reducing the cross-section of the conductor. So stranded conductor with the individual strands insulated against each other are used to achieve the required low resistance while controlling eddy current.

Energy Efficiency in transformer is supported by standards and energy policy instruments. Standards are international or country document describing either test procedures including loss tests, tolerances and guiding on transformers application including lifetime costing, loading or de-rating for harmonic.

Table 1: Main transformer efficiency standards [2]

Country/ Region	Standard	Subject
USA	Guide for Determining Energy Efficiency for Distribution Transformer (TP1-1996). National Electrical Manufacturers Association. 1996	Efficiency standards and TOC formula
	Standard Test Method for Measuring the Energy Consumption of Distribution Transformer (TP2-1998). National Electrical Manufactureres Associations. 1998	Efficiency testing methodology
International	Power transformers - Application guide, IEC60076-8: 1997	Desisng, calculation aspects including measurement of losses
Europe	Cenelec 1992, Harmonisation documents HD428, HD 538 oil and dry type transformers	Efficiency standards and cost capitalisation formula
Variety of country standards defining efficiency levels; MEPS in Australia, Canada, China, Japan Mexico, proposed in India and New Zealand, non mandatory in Europe		

2. *Life Cycle Costing*[6]

To perform the economic analysis of the transformer, it is necessary to take into account the total cost during the lifespan of the transformer, in other words, the 'Total Cost of Ownership' (TCO).

Taking only purchase price and the cost of losses into account the TOC can be calculated by the base formula:

$$TCO = PP + (A \times Po) + (B \times Pk) \quad (1)$$

Where:

PP: Purchase price of transformer

A: Assigned cost of no-load losses per watt

Po: Rated no-load loss

B: Assigned cost of load losses per watt

Pk: Rated load loss

Note: *Po and Pk are transformer rated losses. The A and B values depend on the expected loading of the transformer and energy prices.*

The A and B factors are calculated as bellows:

- No-load loss capitalization

$$A = \frac{(1+i)^n - 1}{i(1+i)^n} \times C_{kWh} \times 8760 \quad (2)$$

- Load loss capitalization

$$B = \frac{(1+i)^n - 1}{i(1+i)^n} \times C_{kWh} \times 8760 \times \left(\frac{I_l}{I_r}\right)^2 \quad (3)$$

Where:

i: interest rate (% per year)

n: lifetime (years)

C_{kWh}: Energy cost per kWh (€/kWh)

8760: number of hours in a year (h/year)

I_l: loading current (A)

I_r: rated current (A)

III. METHODOLOGY

The purpose of this report and the objective function of GAMS program were already presented in the introduction.

The figure 1 will show us the overview of methodology from one step to another.

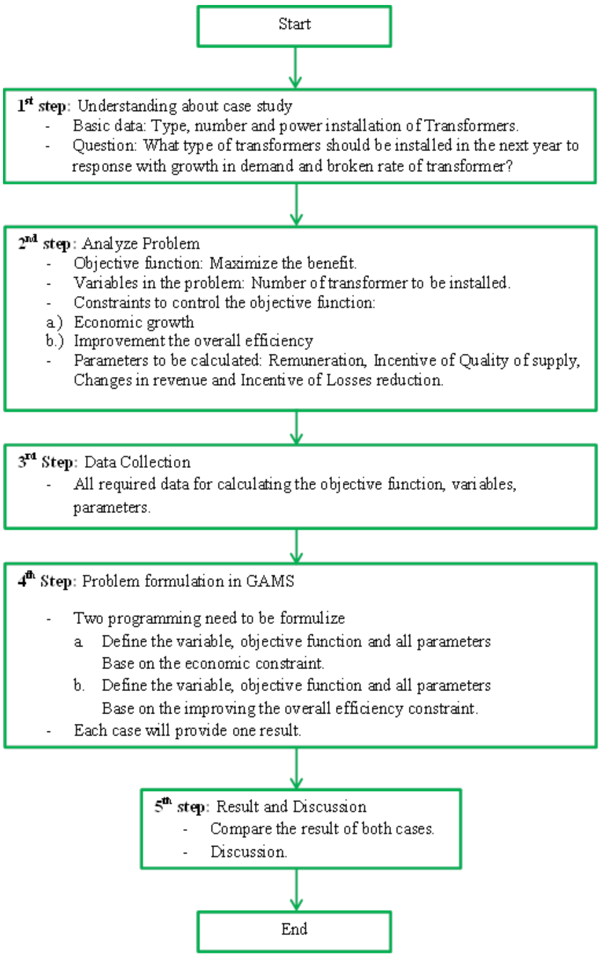

Fig.1: Flow chart of Methodology

The basic data of this case study:

- The power installed: 57.6 MW
- The total number of transformer: 160
- Type of transformers: AB', CC', and AMDT
- The increasing rate of energy demand each year: 5%
- The broken rate of transformer: 5%
- The cost of energy per kWh: 0.0352 €/kWh

Table 2: Basic data of case study

Type	Rated Power(kVA) Pn	No-load Loss(W) Po	Load Loss(W) Pcn	N. of Transformer	Power installation in year 0(kW)
AB'	400.00	750.00	4,600.00	100.00	36,000.00
CC'	400.00	610.00	3,580.00	60.00	21,600.00
AMDT	400.00	240.00	4,600.00	-	-
			Total	**160.00**	**57,600.00**

Base on the information in the table 2, we can calculate the efficiency of each type of transformer by using the formula:

$$\eta = \frac{1}{1 + \frac{2\sqrt{P_0 P_{cn}}}{P_n}} \quad (4)$$

Where:

P_0: the no-load losses

P_{cn}: the load-losses

P_n: rated power

1. *Objective function*

The objective function for this case study is to "Maximize the benefit that we should gain each year after transformer installation to fulfill the increased demand and the replacement of broken transformer" [7].

$$\mathrm{Max}(Z) = R_{n-1} - \left(S \times PF \times h \times \sum_{i=1}^{N} (X_n^i - X_{n-1}^i) \times (1-\eta_i) \right) - \left(\sum_{i=1}^{N} C_i \times \left(X_n^i - \left(X_{n-1}^i \times BR \right) \right) \right) \quad (5)$$

Where:

R_{n-1}: Remuneration cost in year *n-1*

S: Apparent power of each transformer

PF: Power factor of each transformer

h: Hour per year

X^i_n: the total number of transformer type *i* that will be installed in year *n*

X^i_{n-1}: the total number of transformer type *i* that will be installed in year *n-1*

C_i: The unit cost of transformer type *i*

BR: Broken rate of transformer each year

2. *Variables*

The variable X^i_n in this problem is the total number of transformers to be installed in year *n*.

We suppose that the demand growth yearly with increasing rate of 5%. So the total number of transformer in year *n* must be equal or higher than the total amount of transformer in year *n-1* plus demand growth.

$$\sum_{i=1}^{N} X_n^i \geq \sum_{i=1}^{N} X_{n-1}^i (1+DG) \quad (6)$$

Where:

X^i_n: total number of transformer installed in year *n*

X^i_{n-1}: total number of transformer installed in year *n-1*

DG: rate of demand growth (5%)

3. *Constraints*

a.) *Economic Constraint*

The 1st problem formulation, the objective function will be under the control of economic constraint that is based on Spanish RD 222/2008 [8], which stated that the incentive for losses in year *n* is limited by the ±1% of the remuneration in previous year R^i_{n-1}.

$$\left(-0.01 \times R_{n-1}^i\right) \leq \left(Pr \times h \times S \times PF \times \sum_{i=1}^{N} (X_n^i - X_{n-1}^i) \times (1-\eta_i) \right) \leq \left(0.01 \times R_{n-1}^i\right) \quad (7)$$

Where:

R^i_{n-1}: Remuneration in year n-1

Pr: Energy cost per kWh (€/kWh)

S: Rated power (kVA)

PF: Power factor

X^i_n: total number of transformer installed in year *n*

X^i_{n-1}: total number of transformer installed in year *n-1*

η_i: Efficiency of transformer type *i*

b.) *Improvement Energy Efficiency Constraint*

The 2nd problem formulation is to define the objective function with constraint of the improvement of the overall energy efficiency.

$$\left(Pr \times h \times S \times PF \times \sum_{i=1}^{N} (X_n^i) \times (1-\eta_i) \right) \leq \left(Pr \times h \times S \times PF \times \sum_{i=1}^{N} (X_{n-1}^i) \times (1-\eta_i) \right) \times (1+DG) \quad (8)$$

4. *Parameters*

- *Remuneration*

Based on RD222-2008, the annual remuneration during 4 years is determined by the following equations:

$$\begin{aligned}
R_0^i &= R_{base}^i \times (1 + IA_0) \\
R_1^i &= R_0^i \times (1 + IA_1) + Y_0^i + Q_0^i + P_0^i \\
R_2^i &= \left(\left(R_1^i - Q_1^i - P_1^i \right) \times (1 + IA_2) \right) + Y_1^i + Q_1^i + P_1^i \\
R_3^i &= \left(\left(R_2^i - Q_2^i - P_2^i \right) \times (1 + IA_3) \right) + Y_2^i + Q_2^i + P_2^i \\
R_4^i &= \left(\left(R_3^i - Q_3^i - P_3^i \right) \times (1 + IA_4) \right) + Y_3^i + Q_3^i + P_3^i
\end{aligned} \quad (9)$$

Where:

R^i_0: the reference remuneration level adjusted to the calculation year 0

R^i_n: the remuneration attributed to the distribution activity in year *n*

IA_n: the adjustment factor in year *n*

Y^i_{n-1}: the change in allowed revenue in year *n-1*

Q^i_{n-1}: the incentive or penalty term regarding to the quality of energy supply in year *n-1*

P^i_{n-1}: the incentive or penalty term regarding to the loss reduction in year *n-1*

The base remuneration level

$$R_{base}^i = CI_{base}^i + COM_{base}^i + OCD_{base}^i \quad (10)$$

Where:

i: the reference remuneration level

R^i_{base}: the base remuneration level

CI^i_{base}: the remuneration for investments

COM^i_{base}: the remuneration for operation & maintenance costs

OCD^i_{base}: the remuneration for other cost necessary for development of the distribution activities

- *Change in Revenue*

The change in revenue is the amount of money that a company actually receives during a specific period

$$Y^i_{n-1} = \left(R^i_{n-1} - Q^i_{n-2} - P^i_{n-2}\right) \cdot \left(1 + IA_{n-1}\right) \cdot \Delta D^i_{n-1} \cdot Fe^i \quad (11)$$

Where:

Y^i_{n-1}: the change in allowed revenue in year *n-1*

R^i_{n-1}: the remuneration attributed to the distribution activity in year *n-1*

Q^i_{n-2}: the incentive or penalty term regarding to the quality of energy supply in year *n-2*

P^i_{n-2}: the incentive or penalty term regarding to the loss reduction in year *n-2*

ΔD^i_{n-1}: is the average annual increase in subscriber demand final distribution facilities managed by the distribution company *i* in year *n-1*, once corrected for working days and temperature, expressed as an integer.

Fe^i: is the scale factor applicable to the distribution company *i*. The scale factor will be specific to each distribution company and will be defined by order Minister of Industry, Tourism and Trade, proposal the National Energy Commission, which shall take account the elasticity of investment in distribution firm *i* in terms of energy demand in the range.

- *Incentive of Quality Supply*

The incentive or penalty term regarding to the quality of energy supply in year *n-1* is calculate by the formula below:

$$Q^i_{n-1} = 0.03 \times R^i_{n-1}\left(\beta^i_U \cdot X^i_U + \beta^i_{SU} \cdot X^i_{SU} + \beta^i_{RC} \cdot X^i_{RC} + \beta^i_{RD} \cdot X^i_{RD}\right) \quad (12)$$

Where:

Q^i_{n-1}: the incentive or penalty term regarding to the quality of energy supply in year *n-1*

R^i_{n-1}: the remuneration attributed to the distribution activity in year *n-1*

$\beta^i_{U}, \beta^i_{SU}, \beta^i_{RC}, \beta^i_{RD}$: the weighting factor of the urban, semi-urban, concentrated rural, dispersed rural for the purposes of quality incentive for distribution company *i*

$X^i_U; X^i_{SU}; X^i_{RC}; X^i_{RC}$, is an indicator of quality compliance in urban, semi-urban, concentrated rural, dispersed rural areas where the company distributes *i*, in year *n-1*.

- *Incentive to Losses Reduction*

For the incentive for losses reduction in year *n* is limited to ±*x*% of the remuneration in year *n-1* can be calculate by the formula below:

$$P^i_{n-1} = 0.8 \cdot Pr \cdot \left(Eperd^i_{obj,n-1} - Eperd^i_{real,n-1}\right) \cdot \left(E^i_{pf} + E^i_g\right) \quad (13)$$

Where:

Pr: Energy cost in Euro per kWh (€/kWh)

$Eperd^i_{obj,n-1}$: objective losses of distribution company *i* in year *n-1*

$$Eperd^i_{real,n-1} = \frac{\left(E^i_{pf} + E^i_g\right) - E^i_f}{\left(E^i_{pf} + E^i_g\right)} \quad (14)$$

Where:

E^i_{pf}: is the energy measured in the border points in the year *n-1* expressed in kWh.

E^i_g: energy is generated in year *n-1* facilities connected to their networks expressed in kWh.

E^i_f: energy is invoiced the year *n-1* clients connected to their networks expressed in kWh

IV. RESULTS AND DISCUSSION

In this project, the problem formulation in GAMS is analyzed under two constraints:

a.) Economic constraint based on RD222/2008

b.) Improvement overall efficiency constraint

Each constraint provided one result. As the objective of this report is focused on the incentives and the potential energy saving of distribution transformers in distribution network, thus the result of the benefit, the number of each type transformer and the incentive of losses reduction are concentrated.

- *Benefit*

The objective functions of this case study in to maximize the benefit in year *n*. The benefit of the economic constraint, was always higher than the improvement energy efficiency because the constraint (a) always installed the transformer type AB' to fulfill the demand growth each year. And transformer AB' costs less expensive than CC' an AMDT.

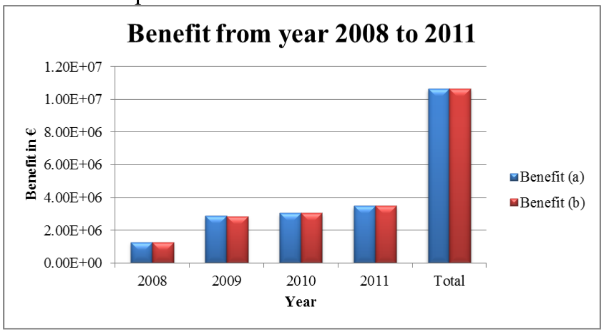

Fig.2: Benefit based on Economic and Energy Efficiency Constraint

- *Number of Transformer*

Even though the total number of transformer installed each year of both case were the same but the type of transformer installed were different. As transformer type AB' costs lower than other. So for case (a), the number of transformer type AB' always increased from year to year to fulfill the demand growth and were used for replacement the broken transformer while the number of transformer CC' decreased yearly due to broken and the AMDT transformer remained at zero value.

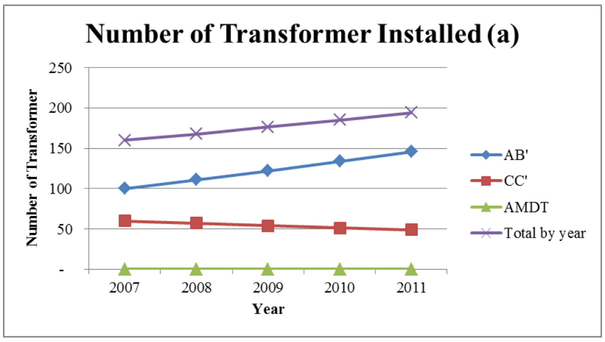

Fig.4.2: Number of transformer based on constraint (a)

In contrast, in order to improve the overall energy efficiency, the transformers AMDT were installed and also the number of AB' and CC' were varied from one year to another.

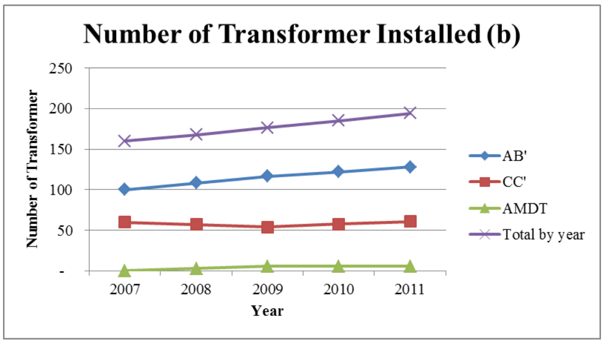

Fig.3: Number of transformer based on constraint (b)

- *Incentive of Losses Reduction*

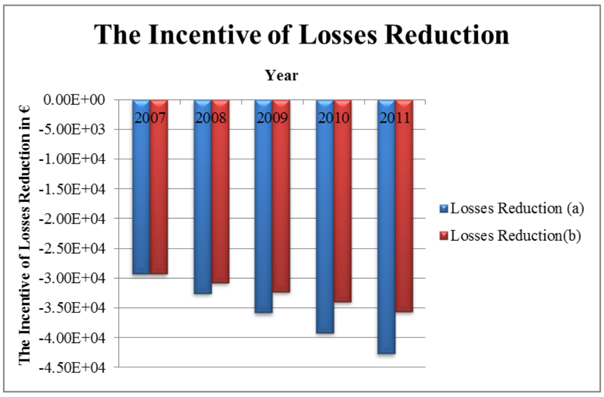

Fig.4: The incentive of losses redution based on constraint (a) and constraint (b)

As constraint (b) based on the improvement of overall energy efficiency, thus the total incentive of losses reduction in this case was better than the total penalty of losses reduction in economic constraint.

V. CONCLUSION

Based on the two problem formulations in GAMS program and the input data in this case study. Two series of result from year 2007 to 2011 has been presented. The total amount of incentive is the different between the total benefit of economic constraint and the total benefit of the improvement overall energy efficiency constraint. The total incentive in this project is *7,100.00 €*. The total amount of potential energy saving in this project is calculated by comparing the energy losses in the improvement energy efficiency constraint with the total losses of the economic constraint. The total potential saving energy in this case study is *353.71MWh*.

Improvement in the future

The result in this case study in not exactly right. Thus in order to improve the work in this future, we need:

- To apply other type of transformers
- To apply this case study with the exact data
- To apply this case study in other countries
- To take into account about other factor like the life cycle costing
- To consider about the environmental impact in the case study. Then we can equalize the three battle fronts of energy sustainability (Economic growth, Energy Supplies and Environmental Impact)

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