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UNIVERSITAT POLITÈCNICA DE CATALUNYA

Energy Efficiency in Power Transformers

THESIS REPORT

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PREFACE

This Master Thesis enacts as the final step to complete my Energy Engineering degree at Department of Electrical Engineering of Polytechnic University of Catalonia. Starting from the 1st day at UPC until I completed this project, I had met a lot of difficulties but I did it. This is because of the support and assistance of some people around me.

First of all, I would like to thank to all staffs at OMI of UPC, Academic Management officers at EUETIB of UPC, who guided me when my first arrival at UPC. As the education system here is different from my home country, so the 1st year was really hard time for me. Beside education system, I need to learn and adapt the different culture. However, that time was really meaningful and unforgettable time for me.

I would like to thank to my advisor, Professor Joan Rull, who has coordinated me since the 1st year of Master.

The deeply thank to Professor Andreas Sumper, the director of my master thesis for always guiding me and giving support during the thesis. Without whom, it would not have been possible.

Thank you to all professors, the former students and including all my friends and those who helped me achieve this thesis.

Above all, I would like to sincerely express my gratitude to my parents for give me advise, encourage me and support me pursue my post-graduate studies.

I wish them good health, good luck, happiness and success in all missions.

June, 2014

Sorita Kalo

ABSTRACT

The objective of this report is to calculate the amount of incentives in order to achieve the potential energy saving of distribution transformer 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.

CONTENTS

LIST OF ABBREVIATIONS

CSA:	Cross Section Area
GAMS:	The General Algebraic Modeling System
IPC:	Consumer Price Index
IPRI:	Industrial Price Index
IRR:	Internal Rate of Return
MEPS:	Minimum Energy Performance Standard
MV:	Medium Voltage
NIEPI:	Number of Equivalent Power Installed (Número de interrupciones equivalente de la potencia instalada)
R&D:	Research and Development
SEEDT:	Strategies for development and diffusion of Energy Efficient Distribution Transformers
T&D:	Transmission and Distribution
TIEPI:	Interruption Time Equivalent Power Installed (Tiempo de Interrupción Equivalente a la Potencia Instalada)
TOC:	Total Cost of Ownership
WEO:	World Energy Outlook

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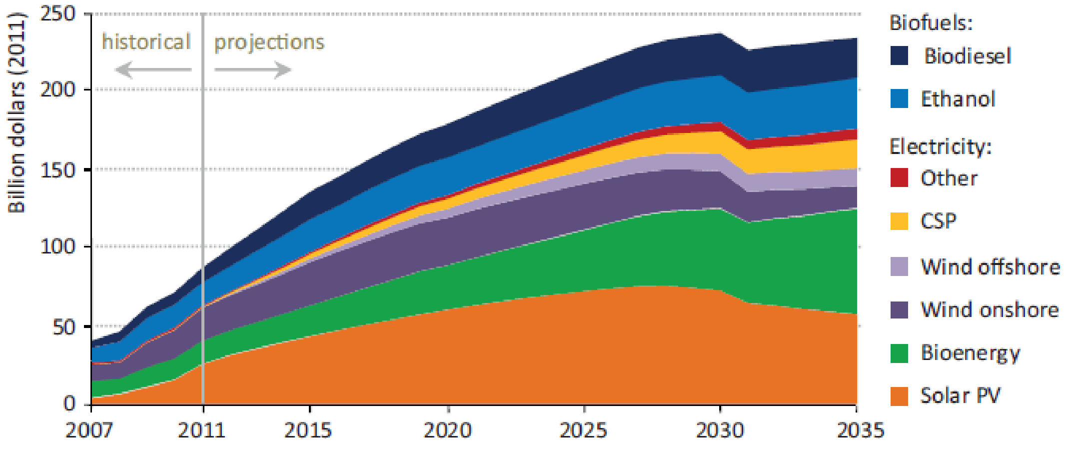
Chapter I:

Introduction

1.1. Background

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. To response with this problem, the R&D of Technologies is the key to equalize the three battle fronts of “Energy sustainability”: energy supply, economic growth and environmental impact. The quote of Energy sustainability is “To provide the world with the energy supplies secure as much as possible, the cost of energy cheap as much as possible and also provide the clean environment as much as possible.

The advanced development technologies and also huge amount of subsidies; are the attractive causes to encourage the businesses investment in renewable technologies. 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. 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.



Notes: Other includes geothermal, marine and small hydro. CSP = Concentrating solar power.

Fig. 1.1: Global renewable energy subsidies by source in the New Policies Scenario [1]

Talking about the distribution network, distribution transformers are the second largest loss-making component after 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 amount of potential energy saving is not only technically advantageous, but also brings the environmental benefit. Up to now four largest economies countries in the world including Australia, China, India and Japan are the most advanced in program of the potential energy saving in distribution transformer. While at the beginning there are seven members: Australia, Canada, China, Europe, India, Japan, and the USA who are willing to improve the transformer in their T&D system.

1.2. Project Description

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].

1.2.1. Objective

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

1.2.2. Case study

So in this project, a case study for Spain will be created. In the base year of investment, the number and power installed of three different types of transformer will be given. After one year of performance, some transformers will break down and the electrical energy demand will be increased. Due to this reason, we need to install the new transformers. So the main question is that: "W*hich type of transformer that we should select and install to fulfill the demand growth?"*

Basically, two problems formulation in GAMs program will be written, under the control of two different constraints:

- 1st constraint: the Economic growth RD222/2008[5]
- 2nd constraint: To improve the overall energy efficiency

After that the result of 1st and 2nd conditions will be presented, the answer of two questions below will be provided:

a. How much is the amount of energy that we can save by applying the high efficiency distribution transformer in distribution network?
b. How much is the amount of incentive that needed to get those potential energy savings?

1.3. Structure of Report

The report of the project will be divided into the chapters as follow:

Chapter 2: Technical and Economic Aspects of Transformer

In order to start the project, firstly the fundamental concepts of transformer will be introduced. It will be followed by causes of losses in transformer and the available technologies nowadays that can be applied in order to improve the energy efficiency of transformer. Beside that in this chapter will be included the economic aspect of transformer like the life cycle costing of transformer.

Chapter 3: Methodology

In this chapter, the overview of methodology, to achieve the amount of incentives and the potential energy saving will be presented. In addition the detail of required information will be shown:

- Basic data of this case study
- Problem formulation: based on two different constraints
- Variables, constraints and the parameters
- Data collections

Chapter 4: Result and Discussion

As there are two problems formulation by using two different constraints in GAMS programs, thus at the end two results will be received.

In this chapter, the description of the result of each problem formulation will be described. At the end of this chapter, the overall discussion of those results will be given.

Conclusion

In this part, the objective of this report will be reviewed. In addition, the achievement of this project will be presented. It will include the amount of incentive and the potential energy saving. Finally, some idea that should be developed in the future to get the better result and the improvement will be given.

Chapter II

Technical and Economic Aspects of Transformer

Chapter II:

Technical and Economic Aspects of Transformer

2.1 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.

2.1.1. Basic principles of transformer

The working principle of a transformer is as follows: when the primary winding connected with the alternating voltage source, electric current changes. A varying electrical current passing through the primary winding causes a changing magnetic field. A changing magnetic field is strengthened by the presence of an iron and iron core is delivered to the secondary coil, so that at the ends of the secondary winding induced EMF will arise. Thus a change in voltage in one winding induces a change in the other.

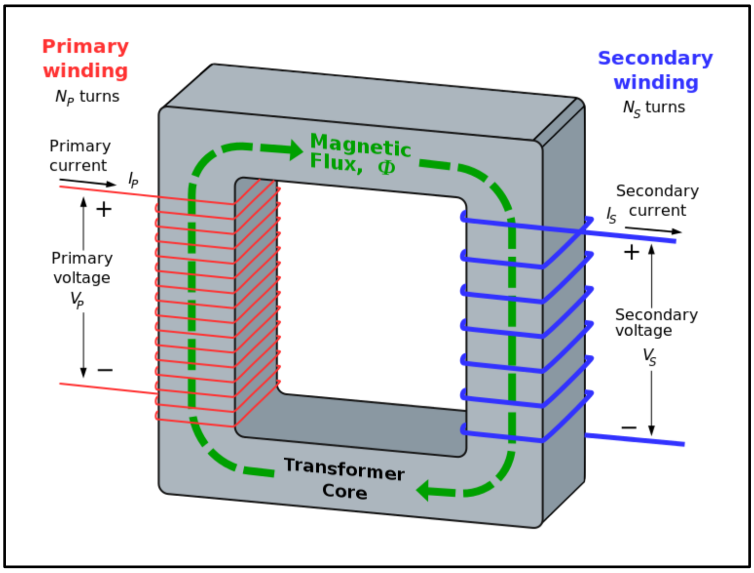


Fig.2.1: Ideal transformer and induction law [6]

2.1.2. Transformer cooling [7]

There are many sources of losses in transformer such as losses in conductors, losses in electrical steel due to the changing flux which is carried, and losses in metallic tank walls and other metallic structures cause by the stray time varying flux. These losses lead to temperatures rise which must be controlled by cooling. The primary cooling media for transformers are oil and air.

In oil cooled transformers, the coils and core are immersed in an oil filled tank. The oil is then circulated through radiators or other types of heat exchanger so that the ultimate cooling medium is the surrounding air or possibly water for some types of heat exchangers. In small distribution transformers, the tank surface in contact with the air provides enough cooling surface so that radiators are not needed. Some time in these units the tank surface area is augmented by means of fins or corrugations.

Fig.2.2: Oil transformer with air convection cooled heat exchangers in the front and at the side [8]

The cooling medium in contact with the coils and core must provide adequate dielectric strength to prevent electrical breakdown or discharge between components at different voltage levels. For this reason, oil immersion is common in higher voltage transformers since oil has a higher breakdown than air. Often one can rely on the natural convection of oil though the windings, driven by buoyancy effects, to provide adequate cooling so that pumping isn't necessary. Air is a more efficient cooling medium when it is blown by means of fans through the windings for air cooled unit.

In some applications, the choice of oil or air is dictated by safety considerations such as the possibility of fires. For units inside buildings, air cooling is common because of the reduced fire hazard. While transformer oil is combustible, there is usually tittle danger of fire since the transformer tank is often sealed from the outside air or the oil surface is blanketed with an inert gas such as nitrogen. Although the flash point of oils is quite high, if excessive heating or sparking occurs inside an oil filled tank, combustible gasses could be released.

Another consideration in the choice of cooling is the weight of the transformer. For mobile transformers such as those used on planes or trains or units designed to be transportable for emergency use, air cooling might be preferred since oil adds considerably to the overall weight. For units are not so restricted, oil is the preferred cooling medium so that one finds oil cooled transformers in general use from large generator or substation units to distribution units on telephone poles.

There are other cooling media which find limited use in certain application. Among these is sulfur hexafluoride gas, usually pressurized. This is a relatively inert gas which has a higher breakdown strength than air and finds use in high voltage units where oil is ruled out for reasons such as those mentioned above and where air doesn't provide enough dielectric strength. Usually when referring to oil cooled transformers, one means that the oil is standard transformer oil. However there are other types of oil which find specialized usage. One of these is silicon oil. This can be used at a higher temperature than standard transformer oil and at a reduced fired hazard.

2.1.3. Losses in transformer[9]

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.

2.1.3.1.No-load losses

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. This losses account around 50% to 80% of total No-load losses. And depend on the type of material used to build a core. Silicon steel has much lower hysteresis than normal steel but amorphous metal has much better performance than silicon steel.

  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 and thus generating heat and take account around 20% to 50% of total No-load losses.

  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.
- Less significant stray and dielectric losses (no more than 1% of total No-load losses): occur in transformer core.

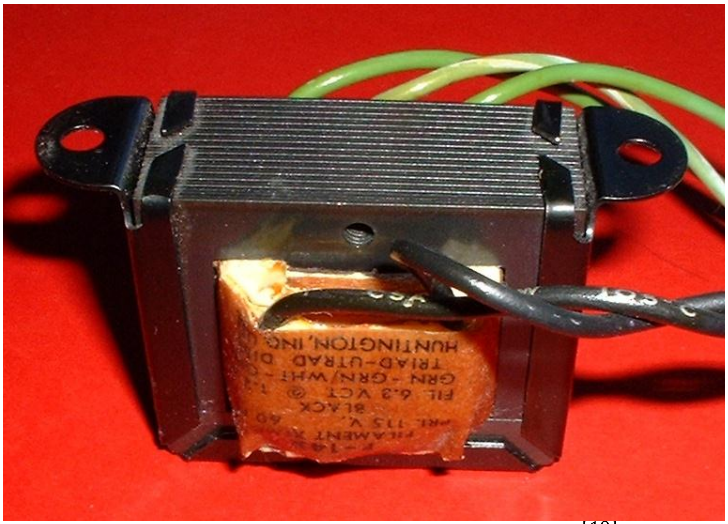


Fig.2.3: Laminated core transformer [10]

2.1.3.2.Load-losses

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. Although core losses also occur in this case, they are not considered part of the load losses. When measuring load losses, the output terminals are shorted to ground and only a small impedance related voltage is necessary to produce the desired full load current. In this case, the losses in the core are small because of the small core flux and do not significantly add to the measured losses.

- 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.

2.1.3.3.Extra losses

These losses are caused by unbalance, harmonics and reactive power.

- Unbalance: Transformers subject to negative sequence voltage transform them in the same way as positive sequence voltages. The behavior with respect to homo-polar voltages depends on the primary and secondary connections and, more particularly, the presence of a neutral conductor. If, for instance, one side has a three-phase four-wire connection, neutral current can flow. If at the other side of the winding is delta-connection, the homo-polar current is transformed into a circulating (and heat-causing) current in the delta. The associated homo-polar magnetic flux passes through constructional parts of the transformer causing by parasitic losses in parts such as the tank, sometimes requiring additional de-rating.
- Extra losses due to harmonics: Non-linear loads, such as power electronic devices, such as variable speed drives on motor systems, computers, UPS systems, TV sets and compact fluorescent lamps, cause harmonic currents on the network. Harmonic voltages are generated in the impedance of the network by the harmonic load currents. Harmonics increase both load and no-load losses due to increased skin effect, eddy current, stray and hysteresis losses.
- Extra losses due to current distortion: The most important of these losses is that due to eddy current losses in the winding; it can be very large and consequently most calculation models ignore the other harmonic induced losses. The precise impact of a harmonic current on load loss depends on the harmonic frequency and the way the transformer is designed. In general, the eddy current loss increases by the square of the frequency and the square of the load current. So, if the load current contained 20%

fifth harmonic, the eddy current loss due to the harmonic current component would be $5^2 \times 0.2^2$ multiplied by the eddy current loss at the fundamental frequency – meaning that the eddy current loss would have doubled.

To avoid excessive heating in transformer supplying harmonic currents, two approaches are used:

1) Reducing the maximum apparent power transferred by the transformer, often called de-rating. To estimate the required de-rating of the transformer, the load’s de-rating factor need to be calculated. This method, used commonly in Europe, is to estimate by how much a standard transformer should be de-rated so that the total loss on harmonic load does not exceed the fundamental design loss. This de-rating parameter is known as “factor K”.

   The transformer de-rating factor is calculated according to the formula:

$$K = \left[1 + \frac{e}{1+e} \left(\frac{I_h}{I} \right)^2 \sum_{n=2}^{n=N} \left(n^q \left(\frac{I_n}{I_1} \right)^2 \right) \right]^{0.5} \tag{2.1}$$

   Where:

   e: the eddy current loss at the fundamental frequency divided by the loss due to a DC current equal to the RMS value of the sinusoidal current, both at reference temperature;

   n: the harmonic order

   I: the RMS value of the sinusoidal current including all harmonics given by

$$I = \left(\sum_{n=1}^{n=N} (I_n)^2 \right)^{0.5} = I_1 \left(\sum_{n=1}^{n=N} \left(\frac{I_n}{I_1} \right)^2 \right)^{0.5} \tag{2.2}$$

   Where:

   I_n: the magnitude of the nth harmonic

   I_1: the magnitude of the fundamental current

   Q: exponential constant that is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round rectangular cross-section conductors in both winding and 1.5 for those with foil low voltage windings.

2) Developing special transformer design rated for non-sinusoidal load currents. This process requires:
   - Analysis and minimizing of the eddy loss in the windings.
   - Calculation of hot sport temperature rise
   - Individual insulation of laminations
   - Increasing the size of core or winding.

   Each manufacturer will use any or all of these technique according to labour rates, production volume and capability of his plant and equipment. These products are sold as “K rated” transformers. During the transformer selection process, the designer should estimate the K factor of the load and select a transformer with the same or higher K factor defined as:

$$K = \sum_{n=1}^{n=n_{max}} I_n^2 n^2 \tag{2.3}$$

- Extra losses due to voltage distortion: The common approach presented above assumes that although the magnetizing current does include harmonics, these are extremely small compared with load current and their effect on the losses in minimal.

  When not ignoring extra losses from voltage harmonics and also those generated in the transformer core the full formula to calculate losses in transformers due to harmonics is as follows:

  $$P_T = 3\sum_n I_n^2 R_n + P_{Fe}\sum\left(\frac{V_n}{V_1}\right)^m \frac{1}{n^{2.6}} \tag{2.4}$$

  Where:

  P_T: losses of transformer due harmonic distortion
  P_{Fe}: fundamental frequency iron losses
  R_n: equivalent copper loss resistance of transformer at nth order
  V_1: fundamental component voltage
  V_n: harmonic voltage of order n
  I_n: harmonic current of order n
  n: order of harmonic
  m: exponent empiric value (assumed to be the value 2)

  The second component in the above equation represents losses in the transformer core caused by voltage distortion. This is a partly empiric formula that may still underestimate core harmonic losses cause by current distortion.

2.1.3.4.Auxiliary Losses

Auxiliary losses caused by using energy to run cooling fans or pumps which help to cool larger transformer. These losses can be avoided if operational temperature is kept low by different loss reduction.

2.1.4. Improving efficiency

To reduce losses in transformers, two elements can be adapted: core and windings. Transformer design is complex, with many of the characteristics of distribution transformers specified in national or international standards. The table 2.1 shows some of the main tradeoffs of Loss Reduction Alternatives.

Load losses, no-load losses and purchase price are all interrelated. Approaches to reduce load losses tend to increase no-load losses and vice versa. For example, a larger core cross-sectional area decreases no-load losses (the flux density core is less), but this requires longer winding conductors and more I^2R load losses.

Table 2.1: Loss Reduction Alternatives [11]

	No-Load Losses	**Load-Losses**	**Cost**
To Decrease No-Load Losses			
- Use lower-loss core materials	Lower	No change*	Higher
- Decrease flux density by			
(1) increasing core CSA	Lower	Higher	Higher
(2) decreasing volts/turn	Lower	Higher	Higher
- Decrease flux path length by decrease conductor CSA	Lower	Higher	Lower
To Decrease No-Load Losses			
- Use lower-loss conductor materials	No change	Lower	Higher
- Decrease current density by increasing conductor CSA	Higher	Lower	Higher
- Decrease current path length by			
(1) decreasing core CSA	Higher	Lower	Lower
(2) increasing volts/turn	Higher	Lower	Higher

* Amorphous core materials would result in higher load-losses

2.1.5. Transformer energy efficiency standard and regulations

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.

Policy instrument are used more to support principle targets, such as energy efficiency. They may include the following:

- A voluntary or mandatory minimum energy efficiency standard
- Labeling
- Incentives from obligations or certificate schemes
- Other financial or fiscal incentives
- Information and motivation
- Tool-kits from buyers
- Energy advice/ audit
- Cooperative procurement
- Support from R&D and pilot or demonstration projects

Although mandatory regulations guarantee the strongest enforcement it is important to mention that energy policy should always acts as a mix of instruments. Regulations usually referred to MEPS (Minimum Energy Performance Standards) for transformer have evolved in many countries over the last decade. Except for China and European proposals of MEPS for “non-distribution” power transformers, such regulations cover distribution transformers, both liquid immersed and dry types of transformer.

The main international normative reference is IEC 60076, Power transformer – Series. The IEEE equivalent standard for IEC 60076-1 (2000) is IEEE C57.12.00 (2006). IEC 60076 gives detailed requirements for transformers for use under defined conditions of altitude ambient temperature for both

- Oil-immersed transformer in IEC 60076-2 and
- Dry-type transformer in IEC 60076-11

The IEC 60076 series consist of the following part relevant to energy efficiency:

- Part1: 1993, General definition of terms
- Part 2: 1993, Temperature rise
- Part 3: 1980, Insulation levels and dielectric tests
- Part 4: 1976, Ability to withstand short-circuit
- Part 7: 2005, Loading guide for oil-immersed power transformers. This part provides recommendations for the specification and loading

of power transformers complying with IEC 60076 from the point of view of operating temperature and thermal ageing. It also provides recommendations for loading above the nameplate rating and guidance for the planner to choose rated quantities for new installations. The use of life time is based on the hot spot temperature in the winding. An increase of the hot spot temperature with 6K is a reduction of the life time by 50%.

- Part 8: 1997, Application guide:

The most important aspects are that the maximum allowable tolerance on the total losses (sum of the load and no-load losses) is +10% of the total losses (IEC 60076-1). This standard in clause IEC 60076-1/7.1 stipulate that the value of losses or efficiency class of the transformer is not mandatory information on rating plate of the transformer.

It is worth mentioning the initiative of Technical Committee n. 14 of IEC, which have initiated a project of new IEC 60076-XX standard: Power transformers- Part XX Energy Efficiency for distribution transformers.

This standard is intended to guide purchasers of power transformers in choosing the most appropriate level of energy efficiency, and the most appropriate method of specifying that efficiency. It will also provide a guide on the loss measurement where not provided for in other standards, and tables of standard losses for certain type of transformers.

As justification it says “Energy efficiency is becoming more and more important as a worldwide issue for electricity transmission and distribution. A standard is needed to provide a method to calculate the energy efficiency according to the way in which the transformer is to be used and the type of transformer, as the best balance between energy use and use of the resources in the construction of the transformer will depend on these factor.

The target of this standard will be:

- Calculation of energy efficiency according to the following parameters:
  - Type of load (inductive, reactive, resistive)
  - Level of rated power
- To provide standard levels of load losses and no-load losses to suit particular efficiency requirements
- The ways in which loss measurement can be done
- The ways in which the uncertainties of measurement can be considered
- Tolerance on guarantees.

❖ **MEPS:** There has been a substantial level of international activity concerning efficiency supporting instruments including MEPS for (distribution) transformers. Comparison of these international efficiency classes is not always obvious because of:

- Differences in electricity distribution systems: grid voltages, grid frequencies (50Hz versus 60Hz), etc.
- Difference in definitions for apparent power rating of the transformer (input power versus output power)
- Difference in load levels at which the efficiency of the transformer is measured (50% load, 100% load, etc.)
- Difference rate size of transformers.

Standards are not limited to efficiency, or loss levels, but may also include total cost of ownership or cost capitalization formulae. Separate documents define testing procedures and conditions. Reference standards on testing are NEMA TP-2 and IEC 60076, acting as the basis for national equivalents.

Table 2.2: 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		

2.2. Economic Aspects

2.2.1. Life-cycle costing[9]

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).

This term includes the purchase price, installation cost, value of the energy losses and maintenance costs over its life, and decommissioning costs. In practice, some simplification can be made. While each transformer will have its own purchase price and loss factors, other costs, such installation, maintenance and decommissioning will be similar for similar technologies and can be eliminated from the calculation. Only when different technologies are compared, e.g. dry-type transformer or oil-cooled transformer, these costs can be considerably different, and should be taken into account.

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

$$\mathrm{TCO} = \mathrm{PP} + (\mathrm{A} \times \mathrm{Po}) + (\mathrm{B} \times \mathrm{Pk}) \tag{2.5}$$

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 choice of factors A and B is difficult, since they depend on the expected loading of transformer, which is often unknown, and energy prices, which are volatile, as well as the interest rate and the anticipated economic lifetime. If the load grows over times, the growth rate must be known or estimated and the applicable energy price over the lifetime must be forecast. Typically, the value of A ranges from less than 1 to 8€/W and B is between 0.2 and 5€/W.

Below we propose a relatively simple method for determining the A and B factor for distribution transformers.

The A and B factors are calculated as bellows:

- No-load loss capitalization

$$A = \frac{(1+i)^n - 1}{i(1+i)^n} \times C_{kWh} \times 8760 \tag{2.6}$$

- Load loss capitalization

$$B = \frac{(1+i)^n - 1}{i(1+i)^n} \times C_{kWh} \times 8760 \times \left(\frac{I_l}{I_r}\right)^2 \tag{2.7}$$

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)

2.2.2. Economic analysis of loss reduction [2]

Tables 2.3, 2.4 and 2.5 show that the energy efficiencies of distribution transformers range from around 94% for a small A-A' transformer, to more than 99% for an amorphous-core distribution transformer with HD 428 C-level losses ('C-AMDT'), the most efficient type available. On average, the loss in a distribution transformer is around 1.5% to 2.0% of the energy transferred. Considering that transformers are working continuously, significant losses can build up. By choosing the right technology, these losses can be reduced by up to 80%.

Table 2.3: Energy saving &return for a high efficiency 100kVA transformer [2]

Efficiency class	Efficiency(%)	Energy saved (kWh/year)	Payback	IRR (% - 25 years)
A-A'	94.71	-	-	
C-C'	96.46	996.00	5.00	20.00
A-AMDT	98.71	2,277.00	7.70	12.00
C-AMDT	98.77	2,310.00	8.60	11.00

Table 2.4: Energy saving &return for high efficiency 400kVA transformer [2]

Efficiency class	Efficiency(%)	Energy saved (kWh/year)	Payback	IRR (% - 25 years)
A-A'	98.04	-	-	-
C-C'	98.64	3,143.00	2.80	36.00
A-AMDT	99.35	6,833.00	5.70	17.00
C-AMDT	99.40	7,085.00	6.60	15.00

Table 2.5: Energy saving & return for high efficiency 1600 kVA transformer [2]

Efficiency class	Efficiency(%)	Energy saved (kWh/year)	Payback	IRR (% - 25 years)
A-A'	98.51	-	-	-
C-C'	98.99	9,759.00	1.40	71.00
A-AMDT	99.38	19,447.00	5.50	18.00
C-AMDT	99.45	20,972.00	5.50	18.00

As the tables show, the pay-back period for investing in high efficiency transformers is relatively short, certainly regarding their long life span (25 - 30 years) are based on 1999 market conditions for Belgium. Prices may vary considerably between markets, and from year to year. Changing an industrial 1600 kVA transformer from a A-A' type to a C-C' type will pay back in 1.4years. The IRR (is defined as the discount factor at which present value of loss reduction over 25 years equals the investment premium in high efficiency transformers) for investments in efficient transformers is consistently above 10% and sometimes as high as 70%. Considering the low risk of the investment, this should make efficient transformers attractive to both industrial companies and grid operators. But in the case of grid operators, there is at present no incentive to invest. Loss reduction then remains the only factor, as they have to be covered by the grid operators, as is the case in most countries.

2.2.3. Externalities[2]

As shown in the previous section, a higher efficiency benefits the owner of the transformer, reducing TCO. On a larger scale, those cost savings are beneficial for the whole economy, enabling the lower cost of production to result in lower tariffs to customers. Each kWh also has an external cost, i.e. the environmental and health costs to society that are not fully reflected in the price of electricity. These externalities originate from the various types of emissions resulting from the combustion of fossil fuel. Apart from CO2, the main offenders are SO2 and NOx which contribute to the acidification of the environment. These pollutants have long range trans-border effects and have therefore become a major concern for most European countries.

Table 2.6: The external cost of electricity for the world generation mix, based on 63 studies [2]

Fuel	External cost US$/kWh	Part of generation	Contribution US$/kWh
Coal	8.30	39.00	3.20
Oil	11.60	8.00	0.90
Gas	3.80	17.00	0.60
Nuclear	1.00	17.00	0.20
Hydro	0.30	17.00	0.10
Renewable	0.3 - 2.9	2.00	-
Total		**100.00**	**5.00**

From table 2.6, the average external cost for the world's generation mix can be estimated at 0.05US$/kWh. Then a saving of 200TWh/year represents, in monetary equivalent, a reduction of 10 billion US$ in environmental cost.

2.2.4. Non-technical losses[2]

Distribution losses are calculated as the difference between electricity paid by clients and energy supplied by a medium voltage transformer to the distribution network. Losses can be technical, or non-technical. Non-technical losses can be:

- Electricity theft
- Invoicing errors
- Bankruptcies of clients
- Measurement errors

Electricity theft is a social problem, and hard to solve, since it addresses a large portion of the population in certain countries. It is not the subject of this paper, which addresses technological solutions to increase efficiency. But care should be taken in interpreting loss figures to distinguish between technical and non-technical losses.

Chapter III

Methodology

Chapter III:

Methodology

3.1. Overview of Methodology

As in the previous chapter, the purpose of this report is to calculate the amount of incentive and the potential energy saving of distribution transformer in distribution network. To get this result, two GAMS programs will be formed, under two constraints: the economic growth and the improvement of overall energy efficiency. The objective function of GAMS program is to define the number of transformer by type to be installed in order to maximize the benefit in each year.

The figure 3.1 will show us the overview of methodology.

First of all, a case study for Spain is formed: the basic data included the total power installed in year zero of the investment; the types of transformer, unit cost and number of transformer are given. Then with the suggested rate of demand growth plus the broken transformer, what type of transformer should be installed to fulfill demand next year?

Second step is problem analysis: the objective function is to select type of transformer to be installed in order to maximize the benefit when the demand grows. Thus the variables of this problem are the number of each type of transformers. In addition, the conditions to control the objective function and variables above must be introduced. Actually, we divided the conditions into two types:

- Necessary condition: is the main constraint to control the objective functions. There are two necessary constraints to apply:
  a.) Economic growth RD222/2008
  b.) Improvement the overall efficiency
  And based on the necessary conditions above, two problem formulations will be developed.
- Satisfied condition: is additional condition to control the variables. The number of each type of transformer to be installed in year *n* must be satisfied the demand growth and broken rate of transformer.

Beside objective function, variables, and conditions, some parameters: the Remuneration, the Incentive of quality supplies, the Incentive of losses reduction and the Change in revenue will be calculated at the end of each year.

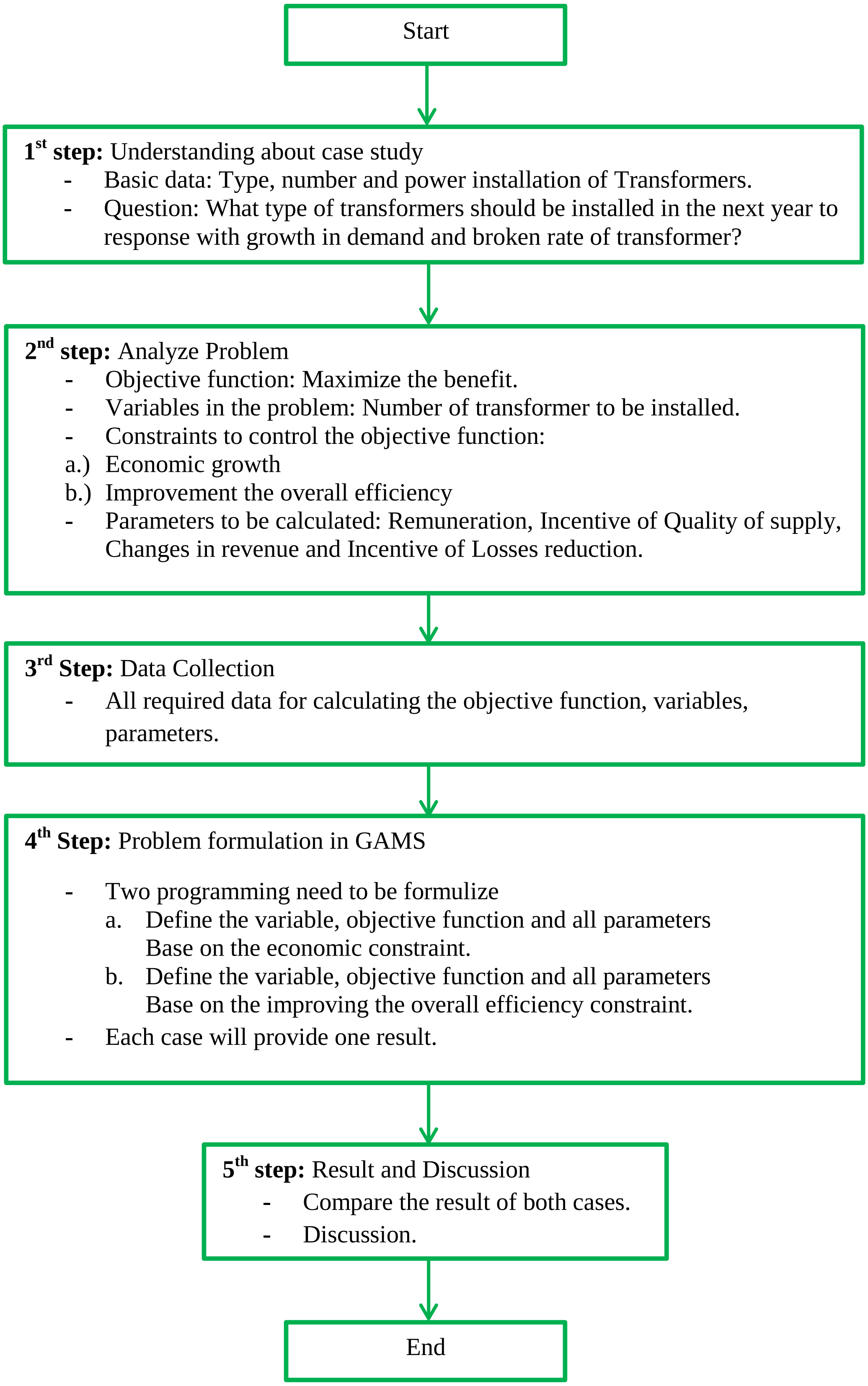
The 3rd step, data collection: the involved data like the adjustment factor; the indicator of quality compliance by zone will be collected after analyzing on the problem included the objective function; the variables; and all parameters.

After defining and collecting all data to solve objective function, variables and parameters, then the next step is to form problem formulation in GAMS. As in the previous statement, there are two necessary conditions which each of them will form a GAMS program. Thus there are two programs will be written in GAMS.

Then we will get two different results:

a.) Result from Economic constraint
b.) Result from the improvement overall energy efficiency

Finally by comparing these two results, the amount of the incentive and the potential energy saving in this project.



Start

1st step: Understanding about case study

- Basic data: Type, number and power installation of Transformers.
- Question: What type of transformers should be installed in the next year to response with growth in demand and broken rate of transformer?

2nd step: Analyze Problem

- Objective function: Maximize the benefit.
- Variables in the problem: Number of transformer to be installed.
- Constraints to control the objective function:

a.) Economic growth
b.) Improvement the overall efficiency

- Parameters to be calculated: Remuneration, Incentive of Quality of supply, Changes in revenue and Incentive of Losses reduction.

3rd Step: Data Collection

- All required data for calculating the objective function, variables, parameters.

4th Step: Problem formulation in GAMS

- Two programming need to be formulize
  a. Define the variable, objective function and all parameters Base on the economic constraint.
  b. Define the variable, objective function and all parameters Base on the improving the overall efficiency constraint.
- Each case will provide one result.

5th step: Result and Discussion

- Compare the result of both cases.
- Discussion.

End

Fig. 3.1: Flow chart of Methodology

3.2. Basic data of case study

In this thesis report, a case study for Spain is formed:

- The power installed: 57.6 MW
- The total number of transformer (with rated power 400kVA): 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 in kWh: 0.0352 €/kWh

Table 3.1: 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 3.1, we can calculate the efficiency of each type of transformer by using the formula:

$$\eta = \frac{1}{1 + \frac{2\sqrt{P_0 P_{cn}}}{P_n}} \tag{3.1}$$

Where:

P_0: the no-load losses
P_{cn}: the load-losses
P_n: rated power

3.3. Analyze Problem

3.3.1. Objective Function

The objective function for this case study is to "Maximize the benefit that should be gained each year after distribution transformer installation to fulfill the increased demand and the replacement of broken transformer".

$$\mathrm{Max}(Z) = R_{n-1} - \left(S \times PF \times h \times \sum_{i=1}^{N} (X_n^i - X_{n-1}^i) \times (1 - \eta_i) \right) - \left(\sum_{i=1}^{N} C_i \times \left(X_n^i - \left(X_{n-1}^i \times BR \right) \right) \right) \tag{3.2}$$

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

3.3.2. Variable

The variable X^i_n in the case study is the total number of distribution transformers to be installed in year *n*. Supposed that the demand growth yearly with increasing rate of 5%. So the total number of distribution transformer in year *n* must be equal or higher than the total amount of transformer in year *n-1* plus demand growth:

$$\sum_{i=1}^{N} X^i_n \geq \sum_{i=1}^{N} X^i_{n-1}\left(1+DG\right) \tag{3.3}$$

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%)

3.3.3. Constraints

Two problem formulations in GAMS program will be written. Each of them depends on one constraint.

3.3.3.1.Economic Constraint

The 1st problem formulation, the objective function will be under the control of economic constraint that is based on Spanish regulation RD 222/2008 [11], 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}.

$$\left(-0.01\times R^i_{n-1}\right) \leq \left(\Pr\times h\times S\times PF\times \sum_{i=1}^{N}(X^i_n - X^i_{n-1})\times(1-\eta_i) \right) \leq \left(0.01\times R^i_{n-1}\right) \tag{3.4}$$

Where:

R^i_{n-1}: Remuneration in year n-1
Pr: Energy cost per (€/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*

3.3.3.2.Energy Efficiency Constraint

The 2nd problem formulation is to define the objective function with constraints of the improvement of the overall energy efficiency. This means that the cost of losses in year *n* must be lower than losses in year *n-1* when there's growth in demand.

$$\left(\Pr\times h\times S\times PF\times \sum_{i=1}^{N}(X^i_n)\times(1-\eta_i) \right) \leq \left(\Pr\times h\times S\times PF\times \sum_{i=1}^{N}(X^i_{n-1})\times(1-\eta_i) \right)\times\left(1+DG\right) \tag{3.5}$$

3.3.4. Parameters

After defining the objective function, variables, of both constraints, we also need to calculate the involved parameters in our case study like: the remuneration, the change in revenue, the incentive of quality of supply and the incentive of losses reduction.

3.3.4.1.Remuneration

In chapter III of the Spanish RD 222/2008, of Ministry of Industry, Tourism and Trade, they stated about "Determining and updating the remuneration activity distribution". In the distribution market, the regulation period is set to be 4 years and the remuneration is different for each company, considering the parameter presented in RD 222/2008 such as the security system, the incentive to quality supply, and loss reduction in distribution networks.

- The base remuneration level

$$R^{i}_{base} = CI^{i}_{base} + COM^{i}_{base} + OCD^{i}_{base} \tag{3.6}$$

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

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

$$\begin{aligned}
R^{i}_{0} &= R^{i}_{base} \times \left(1 + IA_{0}\right) \\
R^{i}_{1} &= R^{i}_{0} \times \left(1 + IA_{1}\right) + Y^{i}_{0} + Q^{i}_{0} + P^{i}_{0} \\
R^{i}_{2} &= \left(\left(R^{i}_{1} - Q^{i}_{1} - P^{i}_{1}\right) \times \left(1 + IA_{2}\right)\right) + Y^{i}_{1} + Q^{i}_{1} + P^{i}_{1} \\
R^{i}_{3} &= \left(\left(R^{i}_{2} - Q^{i}_{2} - P^{i}_{2}\right) \times \left(1 + IA_{3}\right)\right) + Y^{i}_{2} + Q^{i}_{2} + P^{i}_{2} \\
R^{i}_{4} &= \left(\left(R^{i}_{3} - Q^{i}_{3} - P^{i}_{3}\right) \times \left(1 + IA_{4}\right)\right) + Y^{i}_{3} + Q^{i}_{3} + P^{i}_{3}
\end{aligned} \tag{3.7}$$

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*

- **Adjustment factor:** The calculated adjustment required to adjust for the instrument transformer errors of the metering installation.

$$IA_{n} = 0.2 \cdot \left(IPC_{n-1} - X\right) + 0.8 \cdot \left(IPRI_{n-1} - Y\right) \tag{3.8}$$

Where:

IPC_{n-1}: is the change in consumer price index calculated annual calculation in the month of October year *n-1*.

$IPRI_{n-1}$: is the change in producer price index of goods calculated in annual count in October of year *n-1*

X and Y: efficiency factor.
x = 40 and y = 80 based on regulatory period 2009-2012. These factors can be modified by order of the Minister of Industry, Tourism and Trade agreement of the Executive Committee of Minister for Economic Affairs.

3.3.4.2.The change in revenue

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

$$Y^{i}_{n-1} = \left(R^{i}_{n-1} - Q^{i}_{n-2} - P^{i}_{n-2}\right)\cdot\left(1+IA_{n-1}\right)\cdot \Delta D^{i}_{n-1}\cdot Fe^{i} \tag{3.9}$$

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.

3.3.4.3.The 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:

$$Q^{i}_{n-1} = 0.03\times R^{i}_{n-1}\left(\beta^{i}_{U}\cdot X^{i}_{U} + \beta^{i}_{SU}\cdot X^{i}_{SU} + \beta^{i}_{RC}\cdot X^{i}_{RC} + \beta^{i}_{RD}\cdot X^{i}_{RD}\right) \tag{3.10}$$

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*

β^{i}_{U}: the weighting factor of the urban area for the purposes of quality incentive for distribution company *i*

$X^{i}_{U} = \left(1-\frac{TIEPI_{U-real,n-1}}{TIEPI_{U-obj,n-1}}\right)+\left(1-\frac{NIEPI_{U-real,n-1}}{NIEPI_{U-obj,n-1}}\right)$, is an indicator of quality compliance in urban areas where the company distributes *i*, in year *n-1*.

β^{i}_{SU}: the weighting factor of the semi-urban area for the purposes of quality incentive for distribution company *i*

$X^{i}_{SU} = \left(1-\frac{TIEPI_{SU-real,n-1}}{TIEPI_{SU-obj,n-1}}\right)+\left(1-\frac{NIEPI_{SU-real,n-1}}{NIEPI_{SU-obj,n-1}}\right)$, is an indicator of quality compliance in semi-urban areas where the company distributes *i*, in year *n-1*.

β^{i}_{RC}: the weighting factor of the concentrated rural area for the purposes of quality incentive for distribution company *i*

$X^{i}_{RC} = \left(1 - \frac{TIEPI_{RC-real,n-1}}{TIEPI_{RC-obj,n-1}}\right) + \left(1 - \frac{NIEPI_{RC-real,n-1}}{NIEPI_{RC-obj,n-1}}\right)$, is an indicator of quality compliance in concentrated rural areas where the company distributes *i*, in year *n-1*.

β^{i}_{RD}: the weighting factor of the dispersed rural area for the purposes of quality incentive for distribution company *i*

$X^{i}_{RD} = \left(1 - \frac{TIEPI_{RD-real,n-1}}{TIEPI_{RD-obj,n-1}}\right) + \left(1 - \frac{NIEPI_{RD-real,n-1}}{NIEPI_{RD-obj,n-1}}\right)$, is an indicator of quality compliance in the dispersed rural areas where the company distributes *i*, in year *n-1*.

3.3.4.4.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:

$$P^{i}_{n-1} = 0.8 \cdot Pr \cdot \left(Eperd^{i}_{obj,n-1} - Eperd^{i}_{real,n-1}\right) \cdot \left(E^{i}_{pf} + E^{i}_{g}\right) \qquad (3.11)$$

Where:

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

$Eperd^{i}_{obj,n-1}$: objective losses of distribution company *i* in year *n-1* (Therefore one on the sum of the energy measured in the boundary points provided more generated in the facilities connected to its planned network)

$$Eperd^{i}_{real,n-1} = \frac{\left(E^{i}_{pf} + E^{i}_{g}\right) - E^{i}_{f}}{\left(E^{i}_{pf} + E^{i}_{g}\right)}$$

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

3.4. Data Collection

As this project is just formed to model the problem formulation, so some data real data, and some are supposed. Due to some real data is limited, so this case study starts from year 2007 to year 2011.

3.4.1. Power installed in year 2007

These types of distribution transformer are MV transformers; supposed that the power factor of each type of transformer is equal to 0.9.

Table 3.2: Total power installed in year 2007

Type	N. of Tx	Power installation in year 0(kW)
AB'	100.00	36,000.00
CC'	60.00	21,600.00
AMDT	-	-
Total	**160.00**	**57,600.00**

The total power installed is equal to: $P_{installed} = P_n \times PF \times N_{Tx}$ (3.12)

Where:

P_n: rated power
PF: Power factor
N_{Tx}: Number of distribution transformer

So the total distribution transformer installed in year 2007 is 160 with the installed power of 57.6MW.

3.4.2. Remuneration

3.4.2.1.Remuneration in Base Year

In equation 3.6, the base remuneration is equal to:

$$R^i_{base} = CI^i_{base} + COM^i_{base} + OCD^i_{base}$$

Supposed:

R^i_{base}: the base remuneration level
CI^i_{base}: the total cost of transformer
COM^i_{base}: 10% of total cost of transformer
OCD^i_{base}: 5% of total cost of transformer

Table 3.3: Total remuneration in base year (2006)

Type	N. of Tx	Unit Price (€/Transformer)	Total cost(€)	O&M cost(€)	Other cost(€)	Remuneration-base(€)
AB'	100.00	7,064.00	706,400.00	70,640.00	35,320.00	812,360.00
CC'	60.00	7,480.00	448,800.00	44,880.00	22,440.00	516,120.00
AMDT	-	7,730.00	-	-	-	-
		Total	**1,155,200.00**	**115,520.00**	**57,760.00**	**1,328,480.00**

Thus the total remuneration cost in base year is 1.33 Million€.

3.4.2.2.Remuneration in year 2007 to 2011

When the demand grows, the remuneration in equation (3.7) from year 2007 to 2011 must multiply with (1+DG) [11].

$$\begin{aligned}
R^i_0 &= R^i_{base} \times (1+IA_0) \\
R^i_1 &= \left(R^i_0 \times (1+IA_1) + Y^i_0 + Q^i_0 + P^i_0\right) \times \left(1+\Delta D^i_1 \bullet Fe^i\right) \\
R^i_2 &= \left(\left(\left(R^i_1 - Q^i_1 - P^i_1\right) \times (1+IA_2)\right) + Y^i_1 + Q^i_1 + P^i_1\right) \times \left(1+\Delta D^i_2 \bullet Fe^i\right) \\
R^i_3 &= \left(\left(\left(R^i_2 - Q^i_2 - P^i_2\right) \times (1+IA_3)\right) + Y^i_2 + Q^i_2 + P^i_2\right) \times \left(1+\Delta D^i_3 \bullet Fe^i\right) \\
R^i_4 &= \left(\left(\left(R^i_3 - Q^i_3 - P^i_3\right) \times (1+IA_4)\right) + Y^i_3 + Q^i_3 + P^i_3\right) \times \left(1+\Delta D^i_4 \bullet Fe^i\right)
\end{aligned} \tag{3.13}$$

Where:

ΔD^i_n: the average demand growth in year *n* and as the basic data, it equals to 5%

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.

Supposed: $Fe^i = 1$.

3.4.3. Adjustment Factor

Base on equation (3.8) and the real data of IPC [13] and IPRI [14]

$$IA_n = 0.2 \cdot (IPC_{n-1} - X) + 0.8 \cdot (IPRI_{n-1} - Y) \tag{3.8}$$

We can get the adjustment factor of each year as follow:

Table 3.4: Adjustment factor from 2007 to 2011

Year	Adjustment factor
2007	0.0392
2008	0.0512
2009	-0.0406
2010	0.0366
2011	0.054

3.4.4. The Indicator of Quality Compliance by zone

To calculate the incentive or penalty of quality supply, we need to have the indicator of quality compliance by zone.

$$X^i_{Zone} = \left(1 - \frac{TIEPI_{Zone-real,n-1}}{TIEPI_{Zone-obj,n-1}}\right) + \left(1 - \frac{NIEPI_{Zone-real,n-1}}{NIEPI_{Zone-obj,n-1}}\right) \tag{3.14}$$

In our case study we focus on four zones: Urban area, semi-urban area, concentrated rural area and dispersed rural area. So TIEPI [15] and NIEPI [15] in one area are different from the other area.

Table 3.5: The indicator of quality compliance from 2007 to 2011

Year	**Zone**	Indicator of quality compliance (X)
2007	Urban (U)	-0.0461
	Semi-Urban(Su)	-0.1002
	Concentrated rural (Rc)	-0.0808
	Dispersed rural (Rd)	-0.0773
2008	Urban (U)	-0.0696
	Semi-Urban(Su)	-0.0992
	Concentrated rural (Rc)	-0.0866
	Dispersed rural (Rd)	-0.0848
2009	Urban (U)	-0.0345
	Semi-Urban(Su)	-0.0263
	Concentrated rural (Rc)	-0.0335
	Dispersed rural (Rd)	-0.0522
2010	Urban (U)	-0.0318
	Semi-Urban(Su)	-0.0223
	Concentrated rural (Rc)	-0.0403
	Dispersed rural (Rd)	-0.0431
2011	Urban (U)	-0.0918
	Semi-Urban(Su)	-0.1095
	Concentrated rural (Rc)	-0.1253
	Dispersed rural (Rd)	-0.1715

3.4.5. Other Input Data

In order to be able to do the problem formulation, some data in this case study need to be supposed:

- To calculate the change in revenue Y^i_{n-1}, supposed: $Fe^i = 1$. Where Fe^i is the scale factor applicable to the distribution company *i*.
- To calculate the incentive or penalty of quality supply Q^i_{n-1}, supposed the weighting factor of all for zones (urban, semi-urban, concentrated rural and dispersed rural area) is equal to 1.

  $$\beta^i_U = \beta^i_{SU} = \beta^i_{RC} = \beta^i_{RD} = 1$$
- In order to calculate the incentive of losses reduction P^i_{n-1} in equation (3.11), supposed:

Prl: price of energy loss per kWh is 0.025 €/kWh

$Eperd^i_{obj,n-1}$: Efficiency of transformer type CC'

$Eperd^i_{real,n-1}$: Efficiency of transformer type AB',CC' and AMDT

E^i_{pf}: Total energy installed of all types of transformer (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.

$$E^i_g = E^i_{pf} \times \eta_i \tag{3.15}$$

Chapter IV

Result and Discussion

Chapter IV:

Result and Discussion

The objective of this project is to calculate the amount of incentive and potential energy saving of distribution transformer in distribution network. In this project, the problem has been solved by using GAMS program that based on two different constraints:

a.) Economic constraint based on RD222/2008
b.) Improvement overall efficiency

Forming two GAMS programs under the control of two constraints above, will get two series result of objective function, variables, the benefits and the parameters as follow:

4.1. Result

4.1.1. Objective function

The objective functions of this case study in to maximize the benefit in year *n* by installing the new distribution transformer to fulfill the growth of demand. The figure 4.1 shows the benefit of the investment from year 2008 to 2011 and the total benefit. The Benefit (a) represents the result of the objective function under the economic constraints RD222/2008 and Benefit (b) bases on the improvement of overall energy efficiency.

In year 2008, the benefit of constraint (a) is slightly higher than benefit of constraint (b). As case (a) based on economic, the transformer type AB' that costs lower than other types of transformers, continued to increase its installation number to fulfill demand. While in case (b), the transformer type AMDT started to install in order to improve the energy efficiency in the network system.

From year 2008 to 2009, the benefit increased in both cases due to investment for demand growth. However, the benefit in year 2009 of economic constraints is still a little bit higher than the case of the improvement energy efficiency.

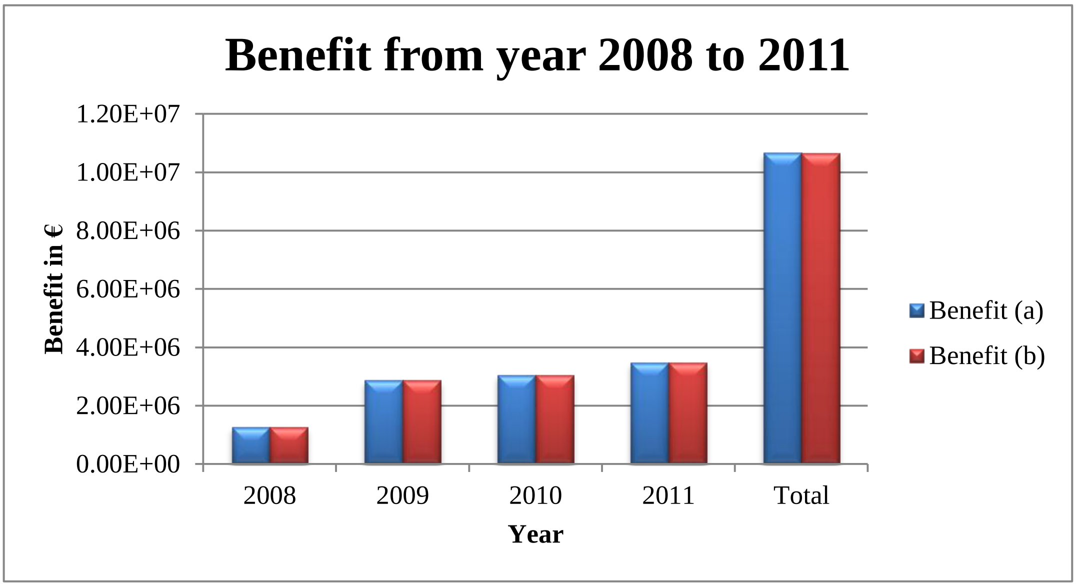


Fig.4.1: Benefit based on Economic and Energy Efficiency Constraint

There’s growth of benefit of constraint(a) and (b) from year 2009 to 2010. But still the constaint (a) provided higher benefit than case(b).

From 2010 to 2011, the situation of benefit that is the objective function continued to increase. And the benefit of case (a) remained higher than the improvement energy efficinecy because case (a) concentrated on the lower cost transfromer- type AB’ rather than transformer type CC’ or AMDT.

The total benefit from year 2008 to 2011 of the economic constriant is 7,100 € higher than the energy efficiency constraint.

4.1.2. Variables

In the previous chapter showed that **t**he number of different type of distribution transformer to be installed in year *n* is the variable to be defined. Remind that, there are three types of transformer in this case study: AB’, CC’ and AMDT. All types of distribution transformer have the same rated power of 400kVA. As we have two different problem formulations. Thus there are two results of the number of each type transformer to be installed in year *n*.

Not different from the objective function that was showed above, the number of the distribution transformer installed case (a) referred to the installation of distribution transformer under the economic constraint, while the constraint (b) means about improving the overall energy efficiency.

In figure 4.2 shows the number of distribution transformer installed from year 2007 to 2011. The year 2007 is the year zero of the investment and we installed 100 transformers type AB’ and 60 transformers type CC’.

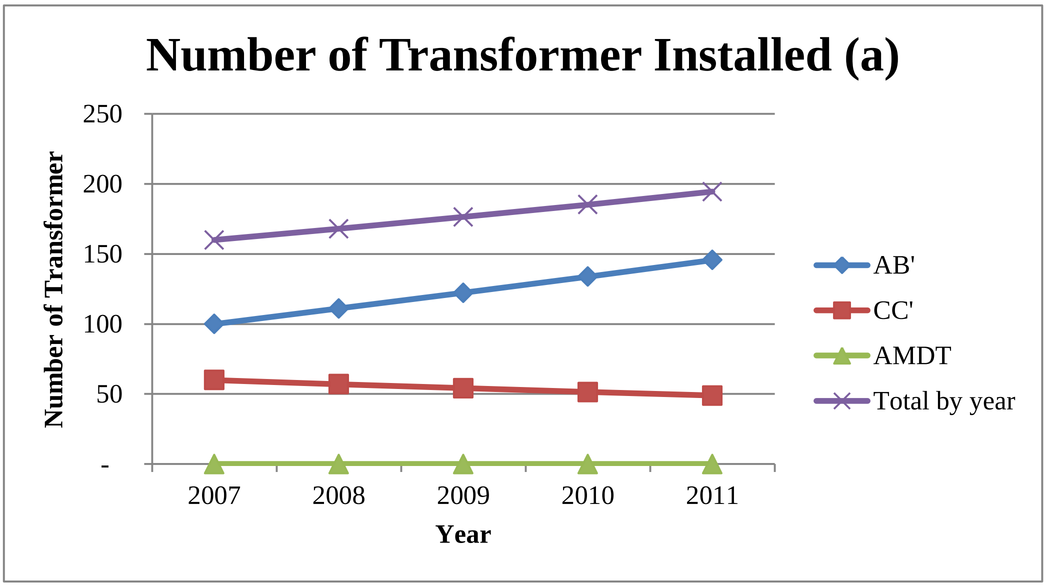


Fig.4.2: Number of transformer based on constraint (a)

After one year of operation some distribution transformers are broken down. So the new distribution transformers need to be installed to replace the broken down and to fill up the demand growth.

From year 2007 to 2011, the graphic of transformer type CC’ continued to drop down from year to year due to the broken rate of transformer. In contrast, the graphicline of transfomer type AB’ grew up yearly to fulfill the growth of demand. However, different from both type of transfrmer, transformer type AMDT remains zerofrom year 2007 to 2011, it means that there’s no transformer of this type has been installed. This is the result of economic constraint, the transformer type AB’, CC’ and AMDT have very slightly different in energy effiency while the cost of is very different. So the transformer type AB’ which is the cheapest transformer among the three type of transformer above is really useful in the economic constraint.

Another result of number of transformer installed that based on the improvement energy effieciency is shown in figure 4.3. Different from the figure 4.2, the graphic of three types of distribution transformer in this figure is varied from year to year.

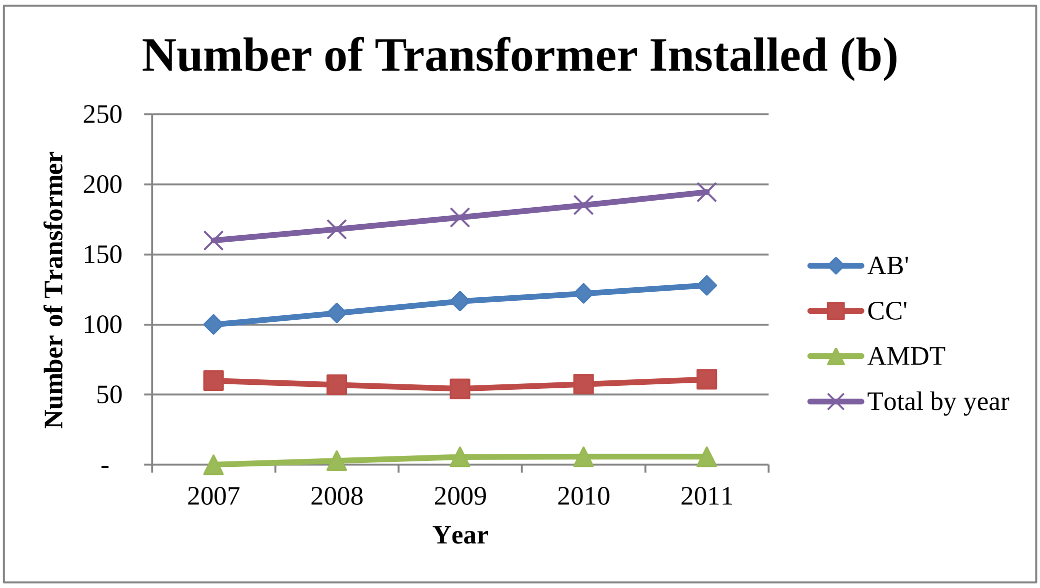


Fig.4.3: Number of transformer based on constraint (b)

Started with year 2007, the installation of distribution transformer type AB’was 100 and transfomer type CC’ was 60.

From 2007 to 2008, the number of distribution transformer type CC’ dropped due to the broken rate while transformer type AMDT was installed in the system first time in 2008. However, the number of transformer type AB’continued to grows. So to fill demand in year 2008, transformer type AB’and AMDT were installed.

The installation of tranformer type AB’in year 2008 to 2009 continued to grow and also the transformer AMDT was very slightly increased. But the tranformer type CC’ continued decreasing. Transformer AB’ still grew in demand due to its low cost. In contrast, the AMDT started growing due to its high efficiency. Thus both type transformers, are useful in order to improve the energy efficiency and also to supply the growth in demand.

From year 2009 to 2011, the transformer AMDT remained the same while the graphic AB’and CC’grew up.

Thus in order to improve the overall energy efficiency, the number of all three types of transformer varied from year to year. This is because the efficiency of AB’, CC’, AMDT is very slightly different while the cost is really different from one type to other.

4.1.3. Parameters

Beside the benefit and the number of distribution transformer, the remuneration, the change in revenue, the incentive of quality supplies and the incentive of losses reduction are the series of parameters to be calculated in the problem formulation.

4.1.3.1. Remuneration

Remuneration is the compensation that one receives in exchange for the work or services performed. In this case study, the remuneration in base year was supposed equal to the total cost of transformer plus the O&P cost and other cost.

The series of remuneration formula already explained in chapter III. The remuneration is mainly in function of the adjustment factor and the average of demand growth of each year. Beside that it is also in functions with the change in revenue, the incentive of quality supplies and the incentive of losses reduction. In figure 4.4 presented the remuneration from the base year of investment (2006) to 2011.

In the base year (2006) and the year zero (2007) of investment, the remuneration of both constraints are the same.

From 2007 to 2008, the remunerations of both cases are dramatically increased simultaneously because the adjustment factor in year 2008 was good.

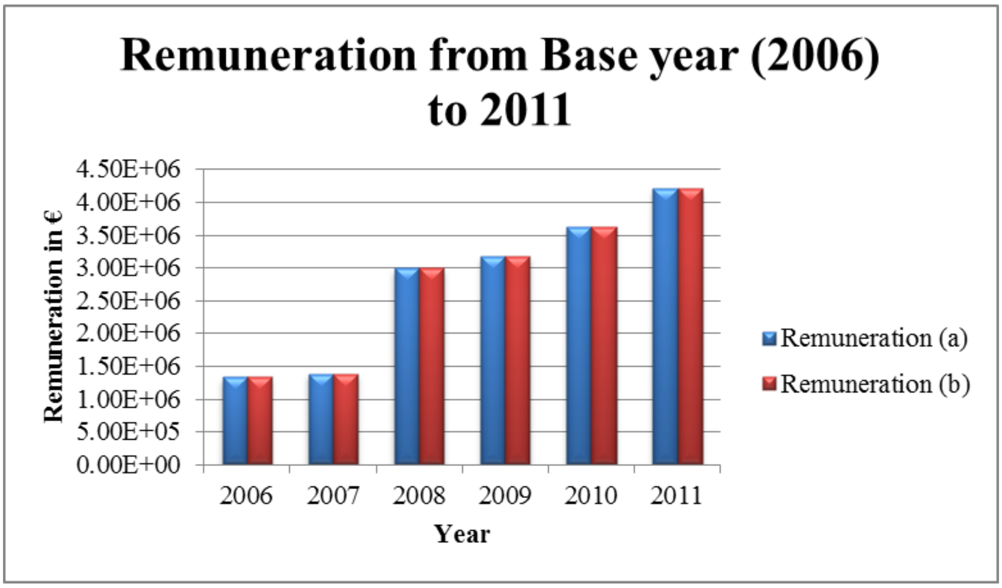


Fig.4.4: Remuneration based on constraint (a) and constraint (b)

The average of demand growth was supposed constant but the adjustment factor was changed from one year to another. In 2009, the adjustment factor was negative. So even though, there was the growth in demand but the remuneration was a bit increased.

From year 2009 to 2011, the remunerations of economic and improvement energy efficiency constraints remained increasing due to the adjustment factor are positive and the demand growth rate supposed the same. However, the remuneration of both case in each year were very slightly different because of other factor like the change in revenue, the incentive of quality and the incentive of losses in both case are different.

4.1.3.2. The Change in Revenue

The change in revenue is in function with the remuneration and adjustment factors, the incentive of quality supplies and the incentive of the losses reduction. The figure 4.5 presented the change in revenue from year 2007 to 2011.

The change in revenue in year 2007 was really high compare to other year because in the year zero of the investment, it was only in function with the remuneration and the adjusment factor while the incentive of quality supplies and the incentive of losses reduction is not in relevant.

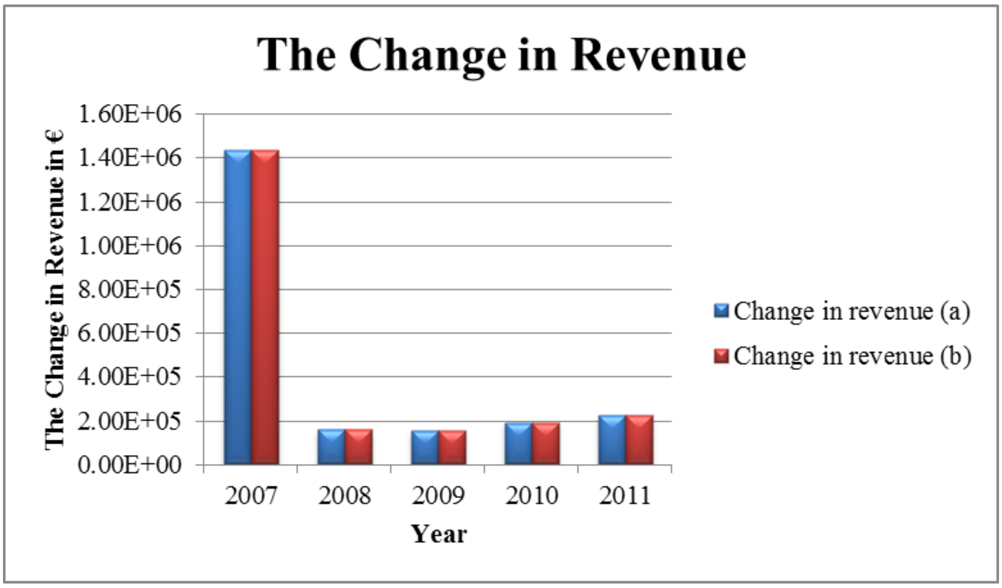


Fig.4.5: The Change in revenue based on constraint (a) and constraint (b)

In year 2008, the change in revenue was include the incentive of losses reduction and the incentive of quality supplies. However, the change in revenue of both case are at the same value in 2008.

The result of the change in revenue in from 2008 to 2009 of both constaints smally decreased due to the negative value of the adjustment factor in year 2009.

From 2009 to 2011, the change revenue in case (a) and (b) contined to increase. However, the change in revenue of economic constraint was always a little bit higher than constraint (b). Because the purpose of case (b) is to improve energy effiency.

4.1.3.3. The Incentive of Quality Supplies

Base on the formula of the incentive of quality supplies in the previous chapter, it is in function with the remuneration and the indicator of quality compliance of each year.

The figure below introduces the result of the result incentive of quality supplies under the control of economic constraint (a) and the constraint (b) of improve overall energy efficiency from year 2007 to 2011.

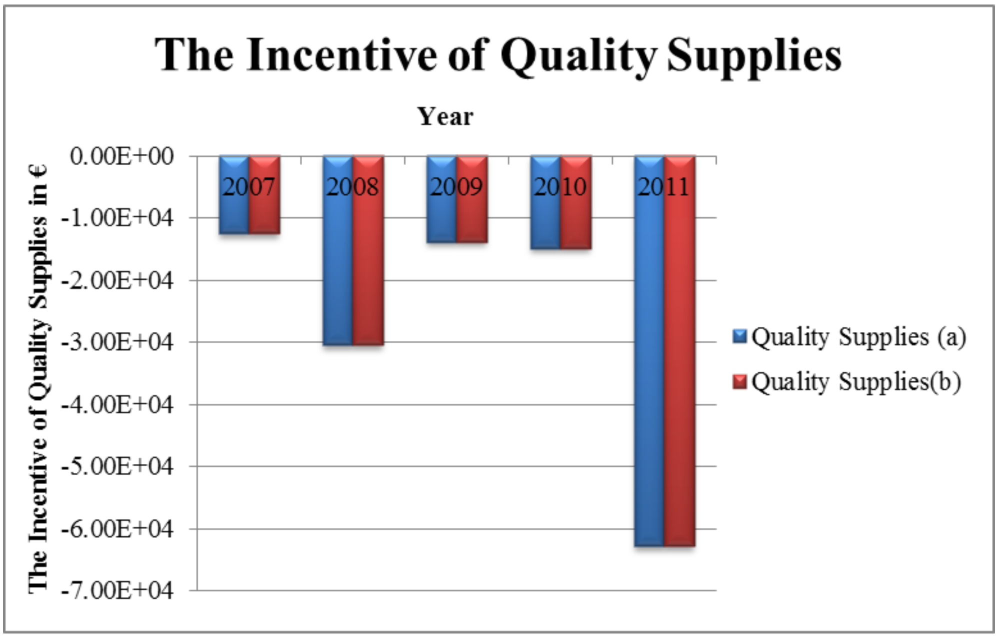


Fig.4.6: The incentive of quality supplies based on constraint (a) and constraint (b)

As the indicator of quality compliance by zone from year 2007 to 2008 always negative, so we should use the term “Penalty of quality supplies” rather than the incentive of quality supplies.

From year 2007 to 2008, the remuneration increased. Due to this reason, the value penalty of quality of supplies in both cases also increased.

However, the penalty of quality supplies drop in year 2009 because the adjustment factor in that year was negative. Other reasons, the indicator of quality compliance by zone in year 2009 was better than 2007 and 2008.

In 2010, indicator of quality compliance by zone remained in good situation, so the penalty of quality supplies in that year was slightly increased from 2009 due to the remuneration increased from 2009 to 2010.

The amount of pentaly of quality supplies in 2011 in both constaints increased simultanously because of the high range of remuneration in year 20011 and the indicator of quality compliance by zone in were worse than in year 2010.

Even though the result of the penalty of quality supplies of economic constraint and improve energy efficiency constraint varies simultaneously from one year to another. But there was slightly different value of the penalty of quality supplies of both cases in each year.

4.1.3.4. The Incentive of Losses Reduction

The incentive of losses reduction is relevant the number of each type of distribution transformer installed each year because the energy efficiency of transformer AB’, CC’ and AMDT are different. The AMDT transformer is the most expensive among these three transformer types and also has higher efficiency than AB’ and CC’.

The figure 4.7 shows the value of the cost of losses reduction of economic constraint and improve energy efficiency constraint. As the results of losses reduction are in negative value, so it is called “the penalty of losses reduction”.

In 2007 the transformers installed in both constraints are the same, the reason why the penalty of losses reductions are equal.

From 2007 to 2011, the penalty of losses reduction based on economic constraints (a) increased. As in the figure 4.2 in the second section indicated that in order to fulfill demand growth and replacement of the broken transformers, transformer type AB' were installed the most while the number of CC' dropped and AMDT remained zero. The transformer type AB', is the lowest energy efficiency transformer among AB', CC' and AMDT. Thus it provided more losses in network than other type of transformer.

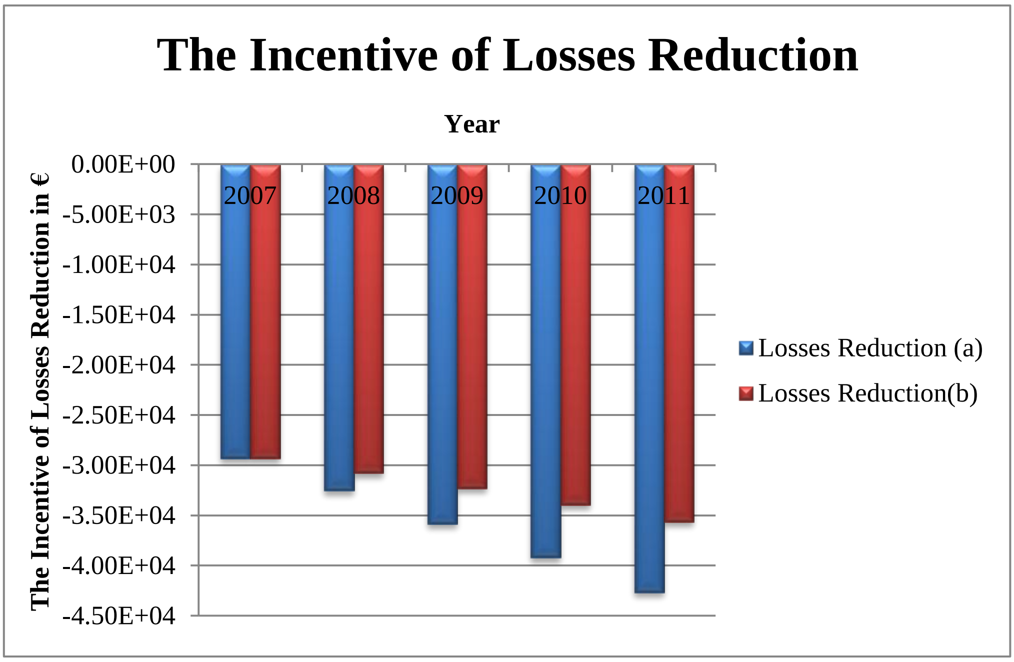


Fig.4.7: The cost of losses redution based on constraint (a) and constraint (b)

The result of the penalty of losses redution in the constraint (b) also increased from 2007 to 2011. Because the demand grew, even there was the installation of the higher efficiency transformer, but as the number of transformer increased, the losses increased too.

Even though the penalty of losses reduction in both cases are increase simultaneously, but the amount of losses redution in the constraint (b) improvement overall energy effiency were always lower than the economic constaint.

4.2. Discussion

In the previous section, each constraint provided one result. However the result of the remuneration, the change in revenue, and the incentive of quality supplies in both cases were almost similar. While the benefit, the number of each type transformer the penalty of losses reduction had the small gap between one to another case.

For the economic constraint, the total benefit was a higher than the improvement overall energy efficiency.

Even though the total number of distribution transformers installed each year of both case were the same but the type of distribution transformer installed were different.

For case (a), transformer type AB’ is cheapest among three types of transformer. So the number of transformer type AB’ always increased from year to year to fulfill the demand growth and was 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. In contrast, in order to improve the overall energy efficiency, the transformer AMDT was installed and also the number of AB’ and CC’ were varied from one year to another.

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

CONCLUSION

The conclusion of this report will be divided into three sections: the objective of the report, the achievement of this report, and suggested idea to improve in the future.

❖ Objective of the report

The objective of this report is *to calculate the amount of incentives in order to achieve the potential of energy saving of the distribution transformer in the distribution network for Spain*.

There are many different ways to get this result. For this report, the amount of the incentive and the potential energy saving by comparing the result of two problem formulations in GAMS under the control of:

a.) Economic constraint based on RD222/2008
b.) Improve overall efficiency

Both of the problem formulations have the same objective function is *to maximize the benefit when demand grows*. And the variables to define, are the number of distribution transformer type AB', CC', and AMDT to be installed each year.

❖ Achievement of this report

Base on the two problem formulations in GAMS program and the input data in this case study based in Spain, two series of result from year 2007 to 2011were achieved.

The total amount of incentive is the difference between the benefit of the economic constraint and the improvement energy efficiency constraint. The total subsides in this project is *7,100.00 €.*

The total amount of potential saving energy in this project is calculated by comparing the energy losses in the improvement energy efficiency with the total losses of the economic constraints. The total potential energy saving in this case study is *353.71MWh*.

Thus the cost of potential saving energy is *0.02€/kWh*.

❖ 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 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)

REFERENCES:

[1]. OECD/IEA, 2012, "*World Energy Outlook 2012*"

[2]. Ronnie Belmans, Jan Declercq, Hans De Keulaner, Katsuaki Furuya, Mayur Karmarkar, Manuel Martinez, Mike McDermott, Ivo Pinkiewicz, 2005, "*The Potential for Global Energy Saving from High Effieincy Distribution Transformers*", European Copper Institute

[3].Polish Copper Promotion Center and European Copper Institute, 2008, "*Selecting Energy Efficient Distribution Transformers/ A Guide for Achieving Least-Cost Solutions*"

[4].http://www.gams.com/ (Date: 18-Feb-2014)

[5]. Paola Pezzini, Oriol Gomis-Bellmunt, Antoni Sudrà-Andreu, Joan Frau-Valentí, 2010, *"Analysis of Energy Efficiency Optimizaton in Distribution Transformer Considering Regulation Constraints"*,CIRED

[6].http://en.wikipedia.org/wiki/File:Transformer3d_col3.svg (Date: 11-May-2014)

[7].Robert M. Del Vecchio, Bertrand Poulin, Pierre T. Feghali, Dilipkumar M. Shah, and Rajendra Ahuja, 2001, "Transformer Design Principles" with application to core-form power transformers, CRC Press.

[8].http://en.wikipedia.org/wiki/File:Transformator_Biomasseheizkraftwerk_Steyr.JPG (Date: 11-May-2014)

[9].Andreas Sumper, Angelo Baggini, 2012, *"Electrical Energy Efficiency: Technologies and Application"*, John Wiley & Sons, Inc.,

[10]. http://en.wikipedia.org/wiki/File:Transformer.filament.agr.jpg (Date: 11-May-2014)

[11].T.A Short, 2003, "Handbook of Electric Power Distribution", CRC Press

[12].http://www.omel.es/files/RD222_2008.pdf (Date: 31-Mar-2014)

[13].http://www.ine.es/varipc/http://www.ine.es/varipc/ (Date: 01-Apr-2014)

[14].http://www.ine.es/en/prensa/ipri_tabla_en.htm (Date: 01-Apr-2014)

[15].https://sede.minetur.gob.es/es-ES/datosabiertos/Paginas/DataSet.aspx?idDataSet=33 (Date: 24-Apr-2014)

ANNEXES

Annex A
GAMS Program based on “Economic Constraint”

```
$Title: Problem Formulation in Distribution Tx System
$ontext
         We need to maximize the benefit for by thinking about
increasing energy efficiency.
         There are three type of Transformer will be used AB', CC' and
AMDT.

         When the demand is increase and/or breakdown distribution
transformer in distribution system,
         Which type of transformer will be installed more to maximize
the profit? and also improve the overall efficiency?
$offtext

SETS
         i Data about each type of Transformer
                                /i1     Rated power(VA)
                                 i2     No-load losses of
Transformer(W)
                                 i3     Load losses of Transformer (W)
                                 i4     Transformer cost(Euro per
Transformer)
                                 i5     Power installed at year
zero(kW)
                                 i6     Active power of
Transformer(kW)
                                 i7     Number of Transformer
installed in year 0/
         j Efficiency classes   /j1     AB'
                                 j2     CC'
                                 j3     AMDT/
         k Adjustment factor each year (from 2006-2010)
                                /k0      year 2007
                                 k1      year 2008
                                 k2      year 2009
                                 k3      year 2010
                                 k4      year 2011/
         m Year
                                /m0     2007
                                 m1     2008
                                 m2     2009
                                 m3     2010
                                 m4     2011/

         n Zone
                                /n1      Urban
                                 n2      Suburban
                                 n3      Concentrated Rural
                                 n4      Dispersed Rural/;
Table   A(i,j) Data about each Transformer
         j1              j2              j3
i1       400000          400000          400000
i2       750             610             240
i3       4600            3580            4600
i4       7064            7480            7730
i5       36000           21600           0
i6       360             360             360
i7       100             60              0;

Table    B(m,n) indicator of quality compliance in each areas by year
```

```
         n1              n2              n3              n4
m0       -0.0461         -0.1002         -0.0808         -0.0773
m1       -0.0696         -0.0992         -0.0866         -0.0848
m2       -0.0345         -0.0263         -0.0335         -0.0522
m3       -0.0318         -0.0223         -0.0403         -0.0431
m4       -0.0918         -0.1095         -0.1253         -0.1715;

Parameter C(k) Adjustment factor each year (from 2007-2011)
                                /k0      0.0392
                                 k1      0.0512
                                 k2      -0.0406
                                 k3      0.0366
                                 k4      0.054/;
Parameter
         EE(j) Energy efficiency of each type of Transformer;
         EE(j) =
1/(1+((2*sqrt((A('i2',j))*(A('i3',j)))))/(A('i1',j)))));
$ontext
         The Remuneration base is equal to the sum of Investment cost,
O&M Cost (10% of Investment cost) and Other cost(5% of investment
cost)
         Where the Investment cost is equal to the Total cost of
Transformer
$offtext

Parameter
         Rbase(j) Remuneration at base year;
         Rbase(j) = A('i4',j)*A('i7',j)*(1+0.15);
SCALAR
         Pr Price Energy per kWh (Euro per kWh)   /0.0352/
         Prl Price of energy lose per kWh /0.025/
         PF Power factor /0.9/
         UF Use factor /0.2/
         h  Utilization time per year /8760/
         x  Incentive for losses /0.01/
         DG Demand growth /0.05/
         BR Broken rate of Transformer/0.05/
         S  Apparent power of Transformer kVA/400/;
$ontext
Business in Year2007
$offtext
Parameter
         X10(j) N. Transformer installed in year 0;
         X10(j) = A('i7',j);
Parameter
         R0(j) Remuneration year 0;
         R0(j) = (1+C('k0'))*Rbase(j);

Parameter
         Y0(j) Revenue in year 0;
         Y0(j) = R0(j)*(1+C('k0'));

Parameter
         Q0(j) Quality in year 0;
         Q0(j)= 0.03*R0(j)*sum(n,B('m0',n));

Parameter
         L0(j) Cost for power losses in year 0;
         L0(j)= Prl*h*((1-EE('j2'))-((A('i5',j)-
(A('i5',j)*EE(j)))/A('i5',j)))*(A('i5',j)+(A('i5',j)*EE(j)));

$ontext
The business in Year 2008
$offtext
```

```
Positive Variable
         X11(j)   Installed power of each type of transformer in year
2008;
Variable
         Z1        Total profit in 2008(Euro);
Equations
         OBJ1     Objective Function
         Min1     Minimum remuneration
         Max1     Maximum remuneration
         InJ11    Power increase for Transformer AB'
         InJ12    Power increase for Transformer CC'
         InJ13    Power increase for Transformer AMDT
         TotalIn1 Total increase;

OBJ1..    Z1 =e= sum(j,R0(j))-(Pr*UF*h*S*PF*(sum(j,((X11(j)-
(X10(j)))*(1-EE(j))))))-(sum(j,(A('i4',j)*(X11(j)-(X10(j)*(1-BR))))));
Min1..    (Pr*UF*h*S*PF*(sum(j,((X11(j)-(X10(j)))*(1-EE(j)))))) =g= (-
x)*(sum(j,(R0(j))));
Max1..    (Pr*UF*h*S*PF*(sum(j,((X11(j)-(X10(j)))*(1-EE(j)))))) =l=
(x)*(sum(j,(R0(j))));
InJ11..     X11('j1') =g= X10('j1')*(1-BR);
InJ12..     X11('j2') =g= X10('j2')*(1-BR);
InJ13..     X11('j3') =g= X10('j3')*(1-BR);
TotalIn1..  sum(j,X11(j)) =g= sum(j,X10(j))*(1+DG);

Model Problem1 /all/;
Solve Problem1 using LP maximizing Z1;
Parameters       R1  Remuneration
                 Y1 Revenue
                 Q1 Quality supply
                 L1 losses reduction;

R1 = ((sum(j,R0(j))*(1+C('k1')))+
sum(j,Y0(j))+sum(j,Q0(j))+sum(j,L0(j)))*(1+DG);
Y1 = (R1-sum(j,L0(j))-sum(j,Q0(j)))*(1+C('k1'))*DG;
Q1 = 0.03*R1*sum(n,B('m1',n));
L1 = Prl*h*((1-EE('j2'))-((sum(j,((X11.l(j))*(1-
EE(j)))))/sum(j,(X11.l(j)))))*(S*PF*(sum(j,(X11.l(j)))+sum(j,((X11.l(j
))*EE(j)))));

Display  R1, Y1, Q1, L1;

$ontext
The business in Year 2009
$offtext
Positive Variable
         X12(j)   Installed power of each type of transformer in year
2009;
Variable
         Z2        Total profit in 2009(Euro);
Equations
         OBJ2     Objective Function
         Min2     Minimum remuneration
         Max2     Maximum remuneration
         InJ21    Power increase for Transformer AB'
         InJ22    Power increase for Transformer CC'
         InJ23    Power increase for Transformer AMDT
         TotalIn2 Total increase;

OBJ2..    Z2 =e= R1-(Pr*UF*h*S*PF*(sum(j,((X12(j)-(X11(j)))*(1-
EE(j))))))-(sum(j,(A('i4',j)*(X12(j)-(X11(j)*(1-BR))))));
Min2..    (Pr*UF*h*S*PF*(sum(j,((X12(j)-(X11(j)))*(1-EE(j)))))) =g= (-
x)*R1;
```

```
Max2..    (Pr*UF*h*S*PF*(sum(j,((X12(j)-(X11(j)))*(1-EE(j)))))) =l=
(x)*R1;
InJ21..     X12('j1') =g= X11('j1')*(1-BR);
InJ22..     X12('j2') =g= X11('j2')*(1-BR);
InJ23..     X12('j3') =g= X11('j3')*(1-BR);
TotalIn2..  sum(j,X12(j)) =g= sum(j,X11(j))*(1+DG);

Model Problem2 /all/;
Solve Problem2 using LP maximizing Z2;
Parameters       R2 Remuneration
                 Y2 Revenue
                 Q2 Quality supply
                 L2 losses reduction;

R2 = (((R1-Q1-L1)*(1+C('k2')))+ Y1+Q1+L1)*(1+DG);
Y2 = (R2-L1-Q1)*(1+C('k2'))*DG;
Q2 = 0.03*R2*sum(n,B('m2',n));
L2 = Prl*h*((1-EE('j2'))-((sum(j,((X12.l(j))*(1-
EE(j)))))/sum(j,(X12.l(j)))))*(S*PF*(sum(j,(X12.l(j)))+sum(j,((X12.l(j
))*EE(j))))));

Display  R2, Y2, Q2, L2;

$ontext
The business in Year 2010
$offtext
Positive Variable
         X13(j)   Installed power of each type of transformer in year
2010;
Variable
         Z3        Total profit in 2010(Euro);
Equations
         OBJ3     Objective Function
         Min3     Minimum remuneration
         Max3     Maximum remuneration
         InJ31    Power increase for Transformer AB'
         InJ32    Power increase for Transformer CC'
         InJ33    Power increase for Transformer AMDT
         TotalIn3 Total increase;

OBJ3..    Z3 =e= R2-(Pr*UF*h*S*PF*(sum(j,((X13(j)-(X12(j)))*(1-
EE(j))))))-(sum(j,(A('i4',j)*(X13(j)-(X12(j)*(1-BR))))));
Min3..    (Pr*UF*h*S*PF*(sum(j,((X13(j)-(X12(j)))*(1-EE(j)))))) =g= (-
x)*R2;
Max3..    (Pr*UF*h*S*PF*(sum(j,((X13(j)-(X12(j)))*(1-EE(j)))))) =l=
(x)*R2;
InJ31..     X13('j1') =g= X12('j1')*(1-BR);
InJ32..     X13('j2') =g= X12('j2')*(1-BR);
InJ33..     X13('j3') =g= X12('j3')*(1-BR);
TotalIn3..  sum(j,X13(j)) =g= sum(j,X12(j))*(1+DG);

Model Problem3 /all/;
Solve Problem3 using LP maximizing Z3;
Parameters       R3 Remuneration
                 Y3 Revenue
                 Q3 Quality supply
                 L3 losses reduction;

R3 = (((R2-Q2-L2)*(1+C('k3')))+ Y2+Q2+L2)*(1+DG);
Y3 = (R3-L2-Q2)*(1+C('k3'))*DG;
Q3 = 0.03*R3*sum(n,B('m3',n));
L3 = Prl*h*((1-EE('j2'))-((sum(j,((X13.l(j))*(1-
EE(j)))))/sum(j,(X13.l(j)))))*(S*PF*(sum(j,(X13.l(j)))+sum(j,((X13.l(j
))*EE(j))))));
```

```
Display  R3, Y3, Q3, L3;

$ontext
The business in Year 2011
$offtext
Positive Variable
         X14(j)   Installed power of each type of transformer in year
2011;
Variable
         Z4        Total profit in 2011(Euro);
Equations
         OBJ4     Objective Function
         Min4     Minimum remuneration
         Max4     Maximum remuneration
         InJ41    Power increase for Transformer AB'
         InJ42    Power increase for Transformer CC'
         InJ43    Power increase for Transformer AMDT
         TotalIn4 Total increase;

OBJ4..    Z4 =e= R3-(Pr*UF*h*S*PF*(sum(j,((X14(j)-(X13(j)))*(1-
EE(j))))))-(sum(j,(A('i4',j)*(X14(j)-(X13(j)*(1-BR))))));
Min4..    (Pr*UF*h*S*PF*(sum(j,((X14(j)-(X13(j)))*(1-EE(j)))))) =g= (-
x)*R3;
Max4..    (Pr*UF*h*S*PF*(sum(j,((X14(j)-(X13(j)))*(1-EE(j)))))) =l=
(x)*R3;
InJ41..     X14('j1') =g= X13('j1')*(1-BR);
InJ42..     X14('j2') =g= X13('j2')*(1-BR);
InJ43..     X14('j3') =g= X13('j3')*(1-BR);
TotalIn4..  sum(j,X14(j)) =g= sum(j,X13(j))*(1+DG);

Model Problem4 /all/;
Solve Problem4 using LP maximizing Z4;
Parameters       R4 Remuneration
                 Y4 Revenue
                 Q4 Quality supply
                 L4 losses reduction;

R4 = (((R3-Q3-L3)*(1+C('k4')))+ Y3+Q3+L3)*(1+DG);
Y4 = (R4-L3-Q3)*(1+C('k4'))*DG;
Q4 = 0.03*R4*sum(n,B('m4',n));
L4 = Prl*h*((1-EE('j2'))-((sum(j,((X14.l(j))*(1-
EE(j)))))/sum(j,(X14.l(j)))))*(S*PF*(sum(j,(X14.l(j)))+sum(j,((X14.l(j
))*EE(j)))));

Display  R4, Y4, Q4, L4;
```

Annex B

GAMS Program based on

“Improvement Overall Energy Efficiency Constraint”

```
$Title: Problem Formulation in Distribution Tx System
$ontext
         We need to maximize the benefit for by thinking about increasing
energy efficiency.
         There are three type of Transformer will be used AB', CC' and
AMDT.

         When the demand is increase and/or breakdown distribution
transformer in distribution system,
         Which type of transformer will be installed more to maximize the
profit? and also improve the overall efficiency?
$offtext

SETS
         i Data about each type of Transformer
                                /i1     Rated power(VA)
                                 i2     No-load losses of Transformer(W)
                                 i3     Load losses of Transformer (W)
                                 i4     Transformer cost(Euro per
Transformer)
                                 i5     Power installed at year zero(kW)
                                 i6     Active power of Transformer(kW)
                                 i7     Number of Transformer installed
in year 0/
         j Efficiency classes   /j1     AB'
                                 j2     CC'
                                 j3     AMDT/
         k Adjustment factor each year (from 2006-2010)
                                /k0      year 2007
                                 k1      year 2008
                                 k2      year 2009
                                 k3      year 2010
                                 k4      year 2011/
         m Year
                                /m0     2007
                                 m1     2008
                                 m2     2009
                                 m3     2010
                                 m4     2011/

         n Zone
                                /n1      Urban
                                 n2      Suburban
                                 n3      Concentrated Rural
                                 n4      Dispersed Rural/;
Table   A(i,j) Data about each Transformer
         j1              j2              j3
i1       400000          400000          400000
i2       750             610             240
i3       4600            3580            4600
i4       7064            7480            7730
```

```
i5       36000           21600           0
i6       360             360             360
i7       100             60              0;

Table    B(m,n) indicator of quality compliance in each areas by year
         n1              n2              n3              n4
m0       -0.0461         -0.1002         -0.0808         -0.0773
m1       -0.0696         -0.0992         -0.0866         -0.0848
m2       -0.0345         -0.0263         -0.0335         -0.0522
m3       -0.0318         -0.0223         -0.0403         -0.0431
m4       -0.0918         -0.1095         -0.1253         -0.1715;

Parameter C(k) Adjustment factor each year (from 2007-2011)
                                /k0      0.0392
                                 k1      0.0512
                                 k2      -0.0406
                                 k3      0.0366
                                 k4      0.054/;
Parameter
         EE(j) Energy efficiency of each type of Transformer;
         EE(j) = 1/(1+((2*sqrt((A('i2',j))*(A('i3',j)))))/(A('i1',j))));
$ontext
         The Remuneration base is equal to the sum of Investment cost,
O&M Cost (10% of Investment cost) and Other cost(5% of investment cost)
         Where the Investment cost is equal to the Total cost of
Transformer
$offtext

Parameter
         Rbase(j) Remuneration at base year;
         Rbase(j) = A('i4',j)*A('i7',j)*(1+0.15);
SCALAR
         Pr Price Energy per kWh (Euro per kWh)   /0.0352/
         Prl Price of energy lose per kWh /0.025/
         PF Power factor /0.9/
         UF Use factor /0.2/
         h  Utilization time per year /8760/
         x  Incentive for losses /0.01/
         DG Demand growth /0.05/
         BR Broken rate of Transformer/0.05/
         S  Apparent power of Transformer kVA/400/;
$ontext
Business in Year2007
$offtext
Parameter
         X10(j) N. Transformer installed in year 0;
         X10(j) = A('i7',j);
Parameter
         R0(j) Remuneration year 0;
         R0(j) =  (1+C('k0'))*Rbase(j);

Parameter
         Y0(j) Revenue in year 0;
         Y0(j) = R0(j)*(1+C('k0'));

Parameter
         Q0(j) Quality in year 0;
         Q0(j)= 0.03*R0(j)*sum(n,B('m0',n));
```

```
Parameter
         L0(j) Cost for power losses in year 0;
         L0(j)= Prl*h*((1-EE('j2'))-((A('i5',j)-
(A('i5',j)*EE(j)))/A('i5',j)))*(A('i5',j)+(A('i5',j)*EE(j)));

$ontext
The business in Year 2008
$offtext
Positive Variable
         X11(j)   Installed power of each type of transformer in year
2008;
Variable
         Z1        Total profit in 2008(Euro);
Equations
         OBJ1     Objective Function
         Imp1     Improve overall efficiency
         InJ11    Power increase for Transformer AB'
         InJ12    Power increase for Transformer CC'
         InJ13    Power increase for Transformer AMDT
         TotalIn1 Total increase;

OBJ1..    Z1 =e= sum(j,R0(j))-(Pr*UF*h*S*PF*(sum(j,((X11(j)-(X10(j)))*(1-
EE(j))))))-(sum(j,(A('i4',j)*(X11(j)-(X10(j)*(1-BR))))));
Imp1..    (Pr*UF*h*S*PF*(sum(j,((X11(j))*(1-EE(j)))))) =l=
(Pr*UF*h*S*PF*(sum(j,((X10(j))*(1-EE(j))))))*(1+DG);
InJ11..     X11('j1') =g= X10('j1')*(1-BR);
InJ12..     X11('j2') =g= X10('j2')*(1-BR);
InJ13..     X11('j3') =g= X10('j3')*(1-BR);
TotalIn1..  sum(j,X11(j)) =g= sum(j,X10(j))*(1+DG);

Model Problem1 /all/;
Solve Problem1 using LP maximizing Z1;
Parameters       R1 Remuneration
                 Y1 Revenue
                 Q1 Quality supply
                 L1 losses reduction;

R1 = ((sum(j,R0(j))*(1+C('k1')))+
sum(j,Y0(j))+sum(j,Q0(j))+sum(j,L0(j)))*(1+DG);
Y1 = (R1-sum(j,L0(j))-sum(j,Q0(j)))*(1+C('k1'))*DG;
Q1 = 0.03*R1*sum(n,B('m1',n));
L1 = Prl*h*((1-EE('j2'))-((sum(j,((X11.l(j))*(1-
EE(j)))))/sum(j,(X11.l(j))))))*(S*PF*(sum(j,(X11.l(j)))+sum(j,((X11.l(j))*
EE(j)))));

Display  R1, Y1, Q1, L1;

$ontext
The business in Year 2009
$offtext
Positive Variable
         X12(j)   Installed power of each type of transformer in year
2009;
Variable
         Z2        Total profit in 2009(Euro);
Equations
         OBJ2     Objective Function
         Imp2     Improve overall efficiency
         InJ21    Power increase for Transformer AB'
```

```
         InJ22    Power increase for Transformer CC'
         InJ23    Power increase for Transformer AMDT
         TotalIn2 Total increase;

OBJ2..    Z2 =e= R1-(Pr*UF*h*S*PF*(sum(j,((X12(j)-(X11(j)))*(1-
EE(j))))))-(sum(j,(A('i4',j)*(X12(j)-(X11(j)*(1-BR))))));
Imp2..    (Pr*UF*h*S*PF*(sum(j,((X12(j))*(1-EE(j)))))) =l=
(Pr*UF*h*S*PF*(sum(j,((X11(j))*(1-EE(j))))))*(1+DG);
InJ21..     X12('j1') =g= X11('j1')*(1-BR);
InJ22..     X12('j2') =g= X11('j2')*(1-BR);
InJ23..     X12('j3') =g= X11('j3')*(1-BR);
TotalIn2..  sum(j,X12(j)) =g= sum(j,X11(j))*(1+DG);

Model Problem2 /all/;
Solve Problem2 using LP maximizing Z2;
Parameters       R2 Remuneration
                 Y2 Revenue
                 Q2 Quality supply
                 L2 losses reduction;

R2 = (((R1-Q1-L1)*(1+C('k2')))+ Y1+Q1+L1)*(1+DG);
Y2 = (R2-L1-Q1)*(1+C('k2'))*DG;
Q2 = 0.03*R2*sum(n,B('m2',n));
L2 = Prl*h*((1-EE('j2'))-((sum(j,((X12.l(j))*(1-
EE(j)))))/sum(j,(X12.l(j))))))*(S*PF*(sum(j,(X12.l(j)))+sum(j,((X12.l(j))*
EE(j)))));

Display  R2, Y2, Q2, L2;

$ontext
The business in Year 2010
$offtext
Positive Variable
         X13(j)   Installed power of each type of transformer in year
2010;
Variable
         Z3        Total profit in 2010(Euro);
Equations
         OBJ3     Objective Function
         Imp3     Improve overall efficiency
         InJ31    Power increase for Transformer AB'
         InJ32    Power increase for Transformer CC'
         InJ33    Power increase for Transformer AMDT
         TotalIn3 Total increase;

OBJ3..    Z3 =e= R2-(Pr*UF*h*S*PF*(sum(j,((X13(j)-(X12(j)))*(1-
EE(j))))))-(sum(j,(A('i4',j)*(X13(j)-(X12(j)*(1-BR))))));
Imp3..    (Pr*UF*h*S*PF*(sum(j,((X13(j))*(1-EE(j)))))) =l=
(Pr*UF*h*S*PF*(sum(j,((X12(j))*(1-EE(j))))))*(1+DG);
InJ31..     X13('j1') =g= X12('j1')*(1-BR);
InJ32..     X13('j2') =g= X12('j2')*(1-BR);
InJ33..     X13('j3') =g= X12('j3')*(1-BR);
TotalIn3..  sum(j,X13(j)) =g= sum(j,X12(j))*(1+DG);

Model Problem3 /all/;
Solve Problem3 using LP maximizing Z3;
Parameters       R3 Remuneration
                 Y3 Revenue
                 Q3 Quality supply
```

```
                 L3 losses reduction;

R3 = (((R2-Q2-L2)*(1+C('k3')))+ Y2+Q2+L2)*(1+DG);
Y3 = (R3-L2-Q2)*(1+C('k3'))*DG;
Q3 = 0.03*R3*sum(n,B('m3',n));
L3 = Prl*h*((1-EE('j2'))-((sum(j,((X13.l(j))*(1-
EE(j)))))/sum(j,(X13.l(j))))))*(S*PF*(sum(j,(X13.l(j)))+sum(j,((X13.l(j))*
EE(j)))));

Display  R3, Y3, Q3, L3;

$ontext
The business in Year 2011
$offtext
Positive Variable
         X14(j)   Installed power of each type of transformer in year
2011;
Variable
         Z4        Total profit in 2011(Euro);
Equations
         OBJ4     Objective Function
         Imp4     Improve overall efficiency
         InJ41    Power increase for Transformer AB'
         InJ42    Power increase for Transformer CC'
         InJ43    Power increase for Transformer AMDT
         TotalIn4 Total increase;

OBJ4..    Z4 =e= R3-(Pr*UF*h*S*PF*(sum(j,((X14(j)-(X13(j)))*(1-
EE(j))))))-(sum(j,(A('i4',j)*(X14(j)-(X13(j)*(1-BR))))));
Imp4..    (Pr*UF*h*S*PF*(sum(j,((X14(j))*(1-EE(j)))))) =l=
(Pr*UF*h*S*PF*(sum(j,((X13(j))*(1-EE(j)))))))*(1+DG);
InJ41..     X14('j1') =g= X13('j1')*(1-BR);
InJ42..     X14('j2') =g= X13('j2')*(1-BR);
InJ43..     X14('j3') =g= X13('j3')*(1-BR);
TotalIn4..  sum(j,X14(j)) =g= sum(j,X13(j))*(1+DG);

Model Problem4 /all/;
Solve Problem4 using LP maximizing Z4;
Parameters       R4 Remuneration
                 Y4 Revenue
                 Q4 Quality supply
                 L4 losses reduction;

R4 = (((R3-Q3-L3)*(1+C('k4')))+ Y3+Q3+L3)*(1+DG);
Y4 = (R4-L3-Q3)*(1+C('k4'))*DG;
Q4 = 0.03*R4*sum(n,B('m4',n));
L4 = Prl*h*((1-EE('j2'))-((sum(j,((X14.l(j))*(1-
EE(j)))))/sum(j,(X14.l(j))))))*(S*PF*(sum(j,(X14.l(j)))+sum(j,((X14.l(j))*
EE(j)))));

Display  R4, Y4, Q4, L4;
```

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Joint Masters Energy Engineering of UB-UPC

Act Assessment Project

Course: FINAL MASTER

Codi UPC: **33563**

Date of defense: Rating:

Student: Sorita Kalo
NIE: Y2542038-T
Title: Energy Efficiency in Power Transfomers

Director: Andreas Sumper
Director:
Speaker:

Court

President:
Members:

Substitutes:

Comment

Signature

Convocation ordinary,	Convocation extraordinary,
Surname, name (President)	Surname, name (President)
Surname, name (Member)	Surname, name (Member)
Surname, name (Member)	Surname, name (Member)