ESCUELA TÉCNICA SUPERIOR DE INGENIERIA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA

QUANTIFICATION OF THE IMPACT OF DISTRIBUTED RESOURCES IN THE OPERATION OF THE ELECTRIC SYSTEM (ROM-MODEL)

Author: Vasco Benito Simões-Coelho
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Madrid
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Introduction

Actual energy system is characterized for centralized management model, big generation units connected to transmission network, however distributed resources are increasing and this could have an economic and technical impact in the operation of the electric system.

With the actual technology development the electrical energy generation will no longer be only profitable for big size units. The latest technological developments are concentrated on small generation units to be installed close to the demand. These units are characterized by high efficiency and preferable use of renewable energy resources.

Taking into account the distributed generation in actual network model would cause a lot of changes in optimization problem formulation, since the amount of information to be collected and centrally treated would considerably increase.

ROM stands for Reliability and Operation Model for Renewable Energy Sources and seeks to study the technical and economic impacts of distributed resources in the operation of the electric system. ROM model[4] has been developed by IIT and has been used in several national and international projects.

The fundamental goal of this project consists in adapting and incorporating in a simplified way distribution network in a model of operation of the electrical system. The network's representation will differentiate resources connected to distribution's networks from resources connected to transmission's networks. This project analyses a case study from Spain in 2012.

The main questions under research in this project are:

- What is the impact of distribution energy losses on locational marginal prices at different voltage levels?
- How do locational marginal prices at voltage levels impact on demand payments and generation incomes?
- How centralized vs. decentralized resources impact the system costs by accounting for distribution losses?

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[4] A description of the ROM model can be found in www.iit.upcomillas.es/aramos/ROM.htm

- How does the economic dispatch of flexible DERs change with and without considering the effect of distribution losses?

Methodology

In order to achieve the main objectives of this project the steps followed were:

- Incorporation of the distribution network in the ROM model using CNMC data

  The reported aggregated values for demand and generation units per voltage levels are disaggregated per each node in the proposed distribution network scheme. That is needed in order to introduce them as input data in the ROM model.
- Calculate the equivalent resistance per each voltage level

  Resistance per each voltage level is needed in order consider losses in distribution network.
- Generation and demand profiles research per voltage level

  Generation and demand profiles are needed in order to distribute by nodes in the proposed distribution network.

- Adapt generation and demand data to network representation

Case studies

In order to answer the main questions under research mentioned in Introduction section, three versions of quadratic losses model are developed (Flexible Cogeneration, Centralized and Decentralized PV).

Additionally initial ROM model ("Single node") is considered for comparison reasons.

Four case studies are developed:

1. Quadratic losses vs. Single node

   Original Single node model closely resembles the current market outcomes of the Spanish system. Single node model considers network as a single node by considering line's losses effect null.

   By introducing losses calculated in quadratic losses model in the single node model's demand input make these two models comparable.

   This comparison pretends to enhance the importance of a better and updated grid modulation in order to reflect more appropriated nodal prices and consequently demand costs and generation remuneration

2. Inflexible Cogeneration vs. Flexible Cogeneration

   It is wanted to enhance the need to create a long-term stable market environment that incentivizes energy efficiency as a critical factor for the uptake of these technologies, as well as strategic planning for energy infrastructure to optimize the use of local energy sources.

What is attempted with flexible cogeneration model is that when price signals are very high (surplus of renewable energy resources) a decrease in CHPs and in hydro pump consumptions occur.

3. Flexible Cogeneration vs. Flexible Cogeneration in Single node model

   This case study wants to study the effects of flexible cogeneration comparing quadratic losses approximation with single node model that considers network as centralized network (losses calculated in quadratic losses model are considered in demand input in order to make these two models comparable).

4. Centralized vs. Decentralized PV

   Lower losses and lower network costs are advantages in decentralized PV power plants, but in the other hand, the investment in a centralized PV power plant is approximately 30% cheaper than a decentralized PV power plant investment (MIT 2015).

   In this case study the comparison between these two options is checked, if the higher investment costs in decentralized PV power plants are compensated with savings in losses.

Results

As for results, the main questions under research can be answered.

- **What is the impact of distribution energy losses on locational marginal prices at different voltage levels?**

  Considering the system as a centralized network despises distribution losses. Even if these losses are considered with linear coefficients, which is the methodology used by the system operator in Spain, the approximation leads to inadequate distribution losses accounting.

  Including distribution of energy losses in ROM model, by lines' resistance as input data, demonstrated that locational marginal prices grow with lower voltage levels quadratically.

- **How do locational marginal prices at voltage levels impact on demand payments and generation incomes?**

  Demand payments and generation incomes depend on the location of demand and generation units in the different nodes of the grid times in the hourly locational marginal prices.

Since locational marginal prices grow with lower voltage level so do the demand payments and generation incomes.

- **How centralized vs. decentralized resources impact the system costs by accounting for distribution losses?**

  The major impacts observed were in the system costs and not in locational marginal prices.

  Decentralized resources have the disadvantage of higher investments in installations, but in the other hand they present benefits in system costs such as reductions in: losses, thermal costs, emissions and at the end on lower market demand payments.

- **How does the economic dispatch of flexible DERs change with and without considering the effect of distribution losses?**

  In flexible cogeneration vs. inflexible cogeneration case study, it was observed that flexible CHPs impact the economic dispatch and reduce thermal costs.

  Considering the effect of distribution losses in the system leads to an increment in incomes of DERs based on locational marginal prices in comparison with single node price.

CUANTIFICACION DEL IMPACTO DE LOS RECUROS DISTRIBUIDOS EN LA OPERACION DEL SISTEMA ELECTRICO

Autor: Vasco Benito Simões-Coelho
Directores: Dr. Tomás Gómez San Román y Dr. José Pablo Chaves Ávila

Introducción

El actual sistema eléctrico se caracteriza por un modelo centralizado, donde las grandes unidades de generación están conectadas a la red de transporte. No obstante cada vez más se observa un incremento de los recursos distribuidos, y esto podría tener un importante impacto tanto a nivel económico como a nivel técnico.

Con el desarrollo tecnológico actual, las grandes unidades de generación no serán las únicas fuentes de energía en salir beneficiadas. Se observa cada vez más una mayor eficiencia y un mayor acercamiento de la generación a la demanda.

Incluir toda la información necesaria para incorporar la generación distribuida en el modelo actual, causaría importantes cambios como la cantidad de información que tendría que ser tratada y la formulación de algoritmo de modelo actual.

ROM (Modelo de Explotación y Fiabilidad para la Generación Renovable) es un modelo que trata de estudiar los impactos técnicos y económicos de los recursos distribuidos en la operación del sistema eléctrico. El modelo ROM[5] está siendo utilizado y mejorado en algunos proyectos nacionales e internacionales.

El objetivo fundamental de este proyecto consiste en adaptar e incorporar, de una manera simplificada, la red de distribución en un modelo de operación del sistema eléctrico. Esta incorporación de la red distinguirá entre recursos conectados a la red de transporte y a la red de distribución. El caso de estudio será España en el año de 2012.

Las cuestiones que se pretenden contestar una vez finalizado el proyecto son las siguientes:

- Cuál es el impacto de considerar las pérdidas de distribución en los precios marginales para diferentes niveles de tensión?
- Como impactan los diferentes precios marginales en los pagos de la demanda y beneficios de los grupos generadores?

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[5] Un descripción del modelo ROM en www.iit.upcomillas.es/aramos/ROM.htm

- Como afectan los recursos centralizados vs. descentralizados en los costes del sistema teniendo en cuenta las pérdidas de distribución?

- Como cambia el despacho económico con recursos distribuidos flexibles considerando o no las perdidas distribuidas?

Metodología

Para alcanzar los objetivos propuestos se siguieron los siguientes pasos:

- Incorporación de la red de distribución en el modelo ROM utilizando datos de CNMC
  Los valores agregados para la demanda y generación por niveles de tensión son desagregados por nodos según el esquema de red propuesto. Esto es necesario para introducir estos datos de entrada en el modelo ROM.
- Calculo de la resistencia equivalente por nivel de tensión
  Este cálculo en necesario para tener en cuenta las pérdidas de distribución en el modelo.
- Búsqueda de perfiles de demanda y generación por niveles de tensión
  Los perfiles de demanda y generación son necesarios para posteriormente distribuirlos en el esquema de red propuesto.
- Adaptación de los perfiles de demanda y generación en el esquema de red

Casos de estudio

Para responder a las cuestiones mencionadas en la Introducción, tres versiones del modelo de pérdidas cuadráticas han sido desarrollados (Cogeneración Flexible, Solar Centralizadas y Solar Descentralizada)

Adicionalmente se utiliza el modelo ROM original (nodo único) por motivos de comparación.

Cuatro casos de estudio han sido preparados:

5. Perdidas cuadráticas vs. Nodo único

   El modelo de nodo único se asemeja al modelo actual del sistema eléctrico Español. Este modelo considera la red como un nodo único, es decir, considerando el efecto de pérdidas en líneas nulo.

   Al introducir las pérdidas calculadas con el modelo de pérdidas cuadráticas en la demanda del modelo de nodo único, se hacen estos dos modelos sean comparables.

   Este caso de estudio pretende demonstrar la necesidad de una mejora en el sistema para que resulten precios más apropiados.

6. Cogeneración Inflexible vs. Cogeneración Flexible

   En este caso de estudio se pretende señalar la importancia de incentivos para la eficiencia de estas tecnologías, y además para una planificación estratégica con el objetivo de optimizar el uso de recursos locales.

7. Cogeneración Flexible vs. Cogeneración Flexible en modelo nodo único

   Este caso de estudio se trata de una mezcla de los dos primeros casos de estudio. Se pretende ver los efectos de considerar las pérdidas de distribución en un modelo en el que la cogeneración en flexible, comparándolo con el modelo de nodo único.

8. Solar Centralizada vs. Solar Descentralizada

   Bajas perdidas y bajos costes de sistema son ventajas de la energía solar descentralizada, pero por otra parte, la inversión en una planta solar centralizada tiene un coste inferior en aproximadamente en un 30% (MIT 2015).

   El caso de estudio pretende comparar estas dos opciones, analizando si la mayor inversión en una instalación descentralizada se compensa con los costes de sistema y menores perdidas.

Resultados

Como resultados, las cuestiones presentadas inicialmente se van a contestar.

- **Cuál es el impacto de considerar las pérdidas de distribución en los precios marginales para diferentes niveles de tensión?**

  Considerando la red en un modelo centralizado no se tienen en cuenta las pérdidas de distribución. Si se consideran coeficientes lineales para las pérdidas, como es el caso del operador del sistema, la aproximación resulta errónea por lo que los precios marginales resultantes no son correctos.

  Al incluir estas pérdidas de distribución se verifica que los precios marginales aumentan cuadráticamente a medida que se baja el nivel de tensión.

- **Como impactan los diferentes precios marginales en los pagos de la demanda y beneficios de los grupos generadores?**

  Los pagos de la demanda y los beneficios de los grupos generadores dependen de sus unidades y de los precios marginales nodales, por lo que al aumentar el precio marginal a medida que se baja de nivel de tensión, también aumentarán los pagos de demanda y beneficios de los grupos generadores.

- **Como afectan los recursos centralizados vs. descentralizados en los costes del sistema teniendo en cuenta las pérdidas de distribución?**

  Los mayores impactos observados fueron en los costes del sistema y no en los precios marginales nodales.

  Los recursos descentralizados tienen desventajas frente a los recursos centralizados en lo que toca a las economías de escala, pero a su vez, presentan beneficios como reducciones en: pérdidas, costes térmicos, emisiones y en pagos de demanda

- **Como cambia el despacho económico con recursos distribuidos flexibles considerando o no las perdidas distribuidas?**

  Se ha observado que el hecho de tener recursos distribuidos flexibles afecta el despacho económico y a su vez en los costes térmicos.

  El considerar las pérdidas distribuidas conlleva a un incremento en los beneficios de los recursos distribuidos teniendo en cuenta que al tener en cuenta estas pérdidas distribuidas el precio marginal aumenta

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MEMORY

INTRODUCTION

Actual energy system is characterized for centralized management model, big generation units connected to transmission network, however distributed resources are increasing and this could have an economic and technical impact in the operation of the electric system.

At this level, until now, the energy is bought from the wholesale market, transported through transmission system and delivered to the customers through distribution system.

Distribution network is used in open-loop mode and has no resources. The flow is unidirectional and consequently centralized management model is the only choice.

With the actual technology development the electrical energy generation will no longer be only profitable for big size units. The latest technological developments are concentrated on small generation units to be installed close to the demand. These units are characterized by high efficiency and preferable use of renewable energy resources.

The big problem is that actual energy system is not modeled to have energy resources at distribution level, at least on a large scale since their impact in the grid is not taken into account.

Figure 1 shows the percentage of installed capacity per technology in 2012 for California, Denmark and Germany.

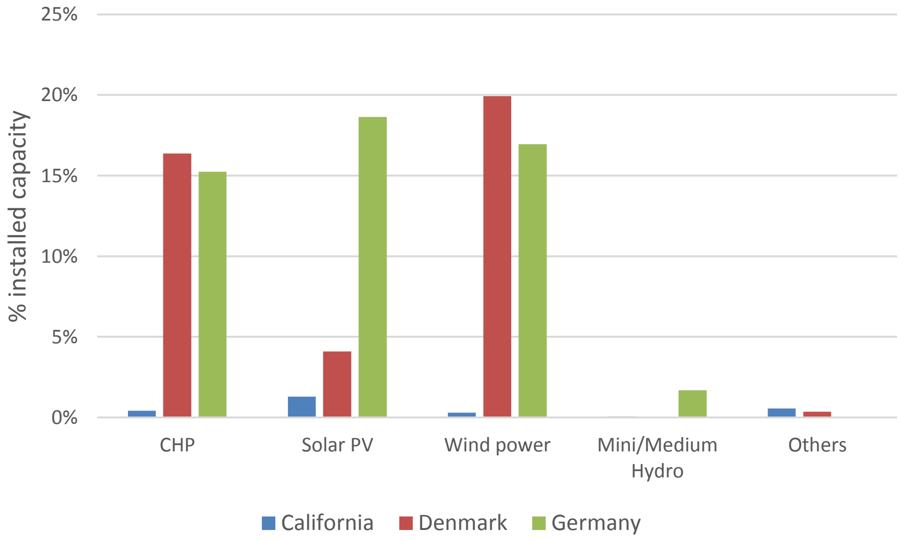


Figure 1 DG installed capacity in California, Denmark and Germany in 2012 (Integrating Distributed Generation: Regulation and Trends in Three Leading Countries. 2014)

Figure 2 shows installed capacity in Spain in 2012.

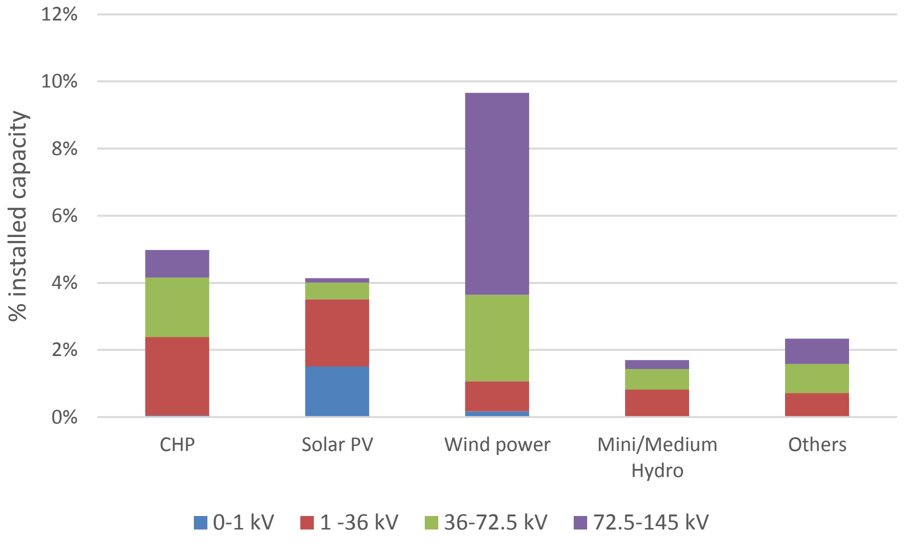


Figure 2 DG installed capacity in Spain in 2012 (CNMC)

Taking into account the distributed generation in actual network model would cause a lot of changes in optimization problem formulation, since the amount of information to be collected and centrally treated would considerably increase.

ROM stands for Reliability and Operation Model for Renewable Energy Sources and seeks to study the technical and economic impacts of distributed resources in the operation of the electric system. ROM model has been developed by IIT and has been used in several national and international projects.

Taking into consideration the physical connections and shared information between system operator and distribution companies, a system of systems based in a stochastic unit commitment framework is designed and a hierarchical optimization algorithm is presented to find optimal operating points of independent systems.

The fundamental goal of this project consists in adapting and incorporating in a simplified way distribution network in a model of operation of the electrical system. The network's representation will differentiate resources connected to distribution's networks from resources connected to transmission's networks. This project analyses a case study from Spain in 2012.

The model used has been adapted in order to incorporate a distribution network representation in the original model. The model has been designed specially to evaluate the technical and economic impact of intermittent generation, meaning, generation units that depend on renewable resources such as wind or solar. These resources are ever more competitive and by so it is expected that their impact increases along the time.

It is considered that the “day before” generation and demand are already known and prediction errors are not taken into account. Ohmic losses will be calculated quadratically to power flows.

With the representation of the distribution network, the impact of the distributed resources in the economic dispatching and operation system can be determined.

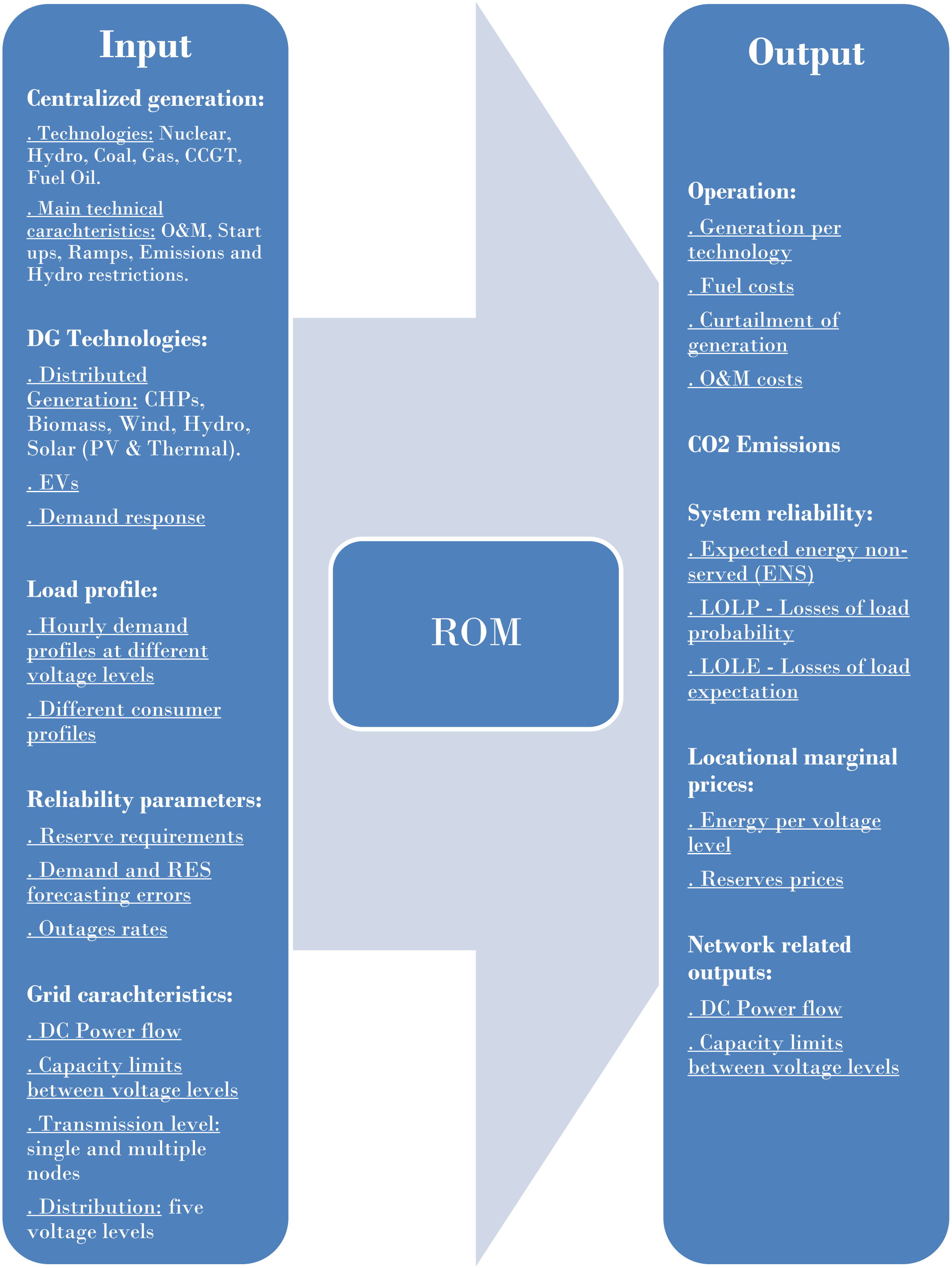
The results are compared with the original model’s optimization problem formulation.

The main questions under research in this project are:

- What is the impact of distribution energy losses on locational marginal prices at different voltage levels?
- How do locational marginal prices at voltage levels impact on demand payments and generation incomes?
- How centralized vs. decentralized resources impact the system costs by accounting for distribution losses?
- How does the economic dispatch of flexible DERs change with and without considering the effect of distribution losses?

Figure 3 represents main inputs and outputs of ROM model as a summary.

In State of the Art progresses in this subject by several institutions are summarized. In methodology section my contribution to this topic is presented. Finally, different case studies will be presented and the results of the simulations will be discussed along with conclusions.



Centralized generation:

. Technologies: Nuclear, Hydro, Coal, Gas, CCGT, Fuel Oil.

. Main technical carachteristics: O&M, Start ups, Ramps, Emissions and Hydro restrictions.

DG Technologies:

. Distributed Generation: CHPs, Biomass, Wind, Hydro, Solar (PV & Thermal).

. EVs

. Demand response

Load profile:

. Hourly demand profiles at different voltage levels

. Different consumer profiles

Reliability parameters:

. Reserve requirements

. Demand and RES forecasting errors

. Outages rates

Grid carachteristics:

. DC Power flow

. Capacity limits between voltage levels

. Transmission level: single and multiple nodes

. Distribution: five voltage levels

Operation:

. Generation per technology

. Fuel costs

. Curtailment of generation

. O&M costs

CO2 Emissions

System reliability:

. Expected energy non-served (ENS)

. LOLP - Losses of load probability

. LOLE - Losses of load expectation

Locational marginal prices:

. Energy per voltage level

. Reserves prices

Network related outputs:

. DC Power flow

. Capacity limits between voltage levels

Figure 3 ROM model Inputs and Outputs

MOTIVATION

The main reason that made me choose this Project in collaboration with IIT comes along with the sustainability and efficiency of the electricity sector.

The realities of climate change mean that sustainable solutions must be implemented in the near term to avoid long-term environmental consequences. In order to meet these challenges and maximize the impact of our efforts, we must consider the sustainability of the energy system as a whole.

A sustainable energy development entails to a financially sustainable economy throughout the world. Poor economies may gain access to free and accessible energy through renewables while also having the opportunity to train worker for jobs that won't be displaced by finite resources.

Knowledge about electrical Engineering and technological tools would be needed to accomplish the project objectives.

Learning how to manage and operate a computational model developed by a research institute motivated me to choose this project and to continue hardworking until complete the initial goals.

Losses predictions are important when it comes to evaluate the efficiency of an energy system. Improving losses approximation means reducing fixed costs, operation costs and an increment in energy sales.

The model's adjustment made in this project (distributed network representation by nodes and different losses approximation) tries to represent in a better way the actual network since the amount of energy resources connected to distribution's networks is increasing and losses calculated by system operator are computed by coefficients which are equal for every hour of the year.

Figure 4 shows distribution and transmission real losses and linear approximation made by the system operator for a period of time. In one hand it is represented linear approximation losses (light green line) and in the other hand real losses (green line).

It is observed that exists a periodicity in linear approximation for everyday of the period represented and that there is a significant difference between linear approximation and real losses.

Coefficients used by system operator as approximation of losses in lines (standard losses) result in inappropriate signal prices. This effect can be evaluated in ROM where marginal prices differentiate resources connected to distribution's network from resources connected to transmission's network.

Inappropriate losses simulation has created a need for additional balancing resources.

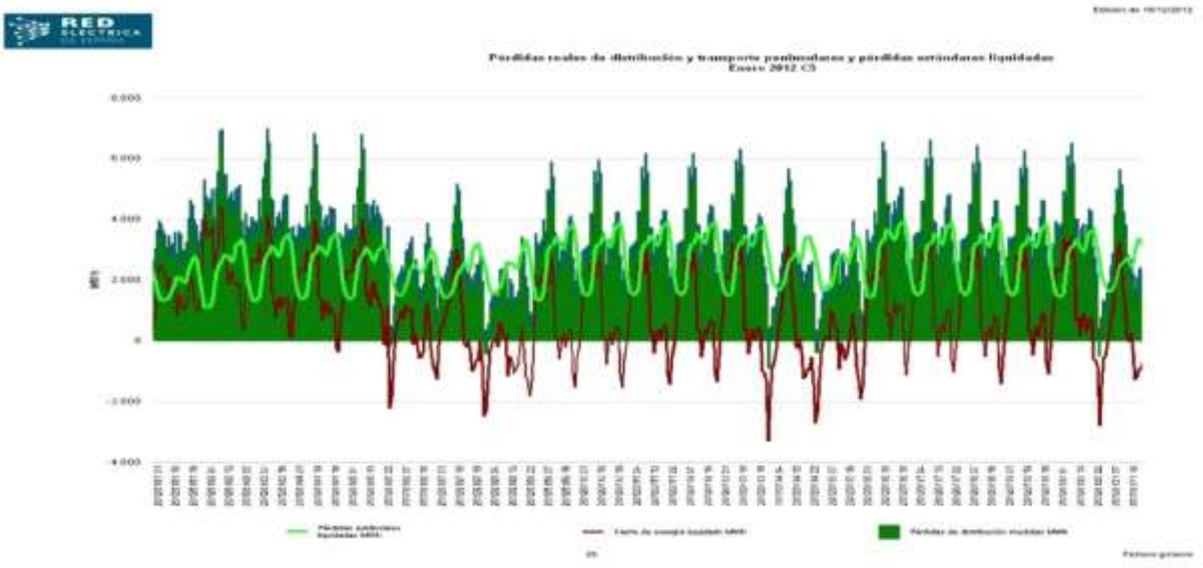


Figure 4 Real distribution and transmission losses for January 2012, in mainland Spain (REE 2012)

The inappropriate distribution losses accounting was mainly due to: Inadequate demand profile, linear losses assumption and the large amount of RES generation that has been connected in distribution networks without considering explicitly their impact on energy losses (Figure 5).

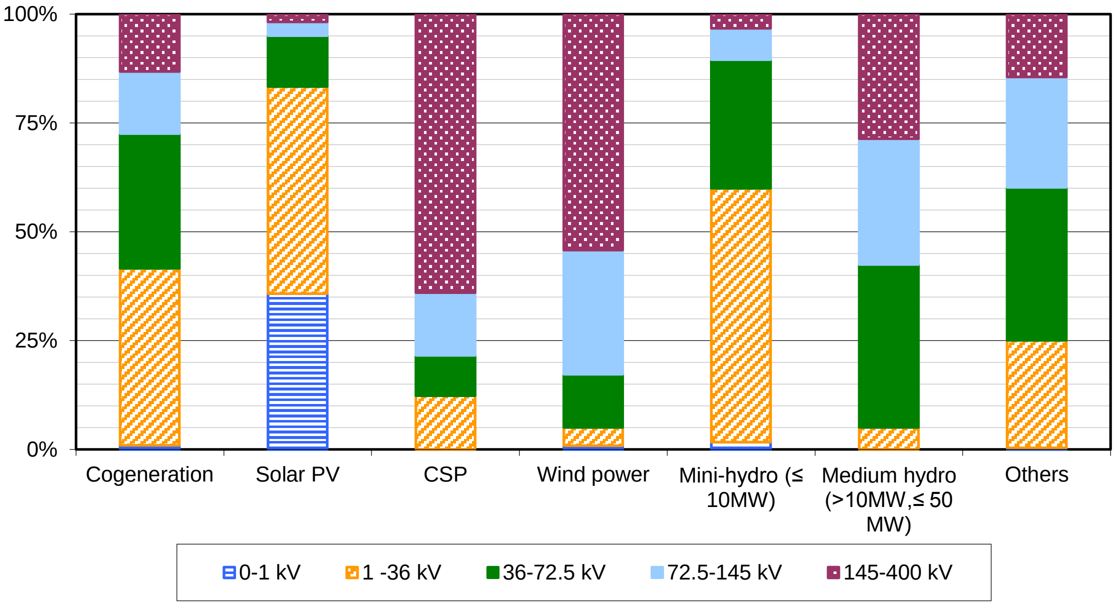


Figure 5 RES Generation by voltage level (CNMC 2012)

This project includes in ROM model a better approximation to real losses.

STATE OF THE ART

The introduction of distributed resources in the energy system can have a significant impact in the operation of the system and so in price signals. In order to evaluate the impact, a representation of the distributed network in economic dispatch is needed.

These effects started to be discussed in literature with models that include signals of prices at distribution's networks levels.

Different studies bring forward the idea of implementation of local prices in distribution's networks levels in order to improve the efficiency of the system. An improvement in the signals of prices is needed to achieve smarter networks and by so achieve a better local coordination (Brandstätt 2012).

The intermittent generation integration into the electrical grid is challenging. One of the biggest problems in the formulation of network's representation is the intermittent generation. With the increasing worldwide wind generation capacity, proper wind power integration into the electrical network becomes more and more important.

Stochastic programming has been researched to deal with the uncertainty of wind power generation output based on scenarios but when multiple IG technologies are located at different nodes in the transmission network, the complexity increases drastically (Unit Commitment with Intermittent Wind Generation via Markovian Analysis with Transmission Capacity Constraints 2012).

In Smart Grid Roadmap Project (ISO Smart Grid Use Case 2010), due to the increase of renewable distributed generation and the existence of loads that will respond on real-time prices, elaborated smart grid roadmap project where the impact of rooftop solar PV and other types of resources that are variable or change based on incentives are a major focus.

One of the smart grid roadmap project goals is to provide real-time "prices to devices" in the form of a grid condition indicator. The challenge of this goal will be to keep the grid stable and its reactions to changing weather conditions such as cloud coverage. Other challenge is to predict the real-time solar generation volatility, depending on weather forecasting process.

In smart grid roadmap project it is pretended to describe how California ISO uses information about non-dispatchable Distributed Energy Resource (DER) to modify their system load forecast. This process helps on decision making to account for non-dispatchable distributed energy resources across a wide range of technologies.

The analysis of the increment of renewable energy sources that could be integrated safely in some countries of the EU, using ROM model, is one of the tasks that involve MERGE[6] project. This project studies the impact of electric vehicles, depending on the different technologies and their peak demand values.

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[6] http://www.ev-merge.eu/

ROM model used in MERGE project modulates Canary's Islands network using a DC load flow study. ROM model with DC load flows has never been used in large scale systems.

This model is currently being used and improved in some Spanish or European research projects:

- TWENTIES[7]. Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions.

- SUSPLAN[8]. Planning for Sustainability: Grid-based renewable energy sources integrated scenarios for national, regional and European levels; optimal path for RES integration, in consideration of security issues and economic competitiveness; implementation strategies for decision makers.

- CENIT-VERDE[9]. National Strategic Consortium in Technical Research:
  - Electric Vehicle. Energy Response Unit.
  - Ecological vehicle. Reality for the reduction of emissions.
  - Spanish vehicle. Recipe for boosting employment.

- Grid Integration of Compressed Air Energy Storage systems (CAES)

- Beyond2020[10]. Design and impact of a harmonized policy for renewable electricity in Europe

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[7] http://www.twenties-project.eu/node/1

[8] http://www.susplan.eu/

[9] http://cenitverde.es/

[10] http://www.res-policy-beyond2020.eu/

METHODOLOGY

As pointed out in the Introduction section, the main objective of this project is to incorporate a simplified model of the distribution network in the ROM algorithm, which is a model to simulate and optimize the operation of the generation and transmission power system. In addition, four case studies are going to be analyzed. In order to accomplish this goal the following steps are followed.

Task
Incorporation of the distribution network in the ROM model using CNMC data
Calculate the equivalent resistance per each voltage level
Generation and demand profiles research per voltage level
Adapt generation and demand data to network representation
Case studies data preparation
Results analysis

Table 1 Table of performed tasks

The reported aggregated values for the whole mainland Spain in the year of 2012 are used as a starting point of this project.

The reported aggregated data is represented in the scheme of Figure 6. These values are reported for six different periods by the Spanish Energy Regulator (Comisión Nacional de Mercados y Competencia - CNMC).

It is important to note that data correspond to energy flows (kWh). For this case study power units are needed (kW), and because of that the duration of each time period is required. In the following tables we can find for the different periods of time the number of hours and days that are represented in each period.

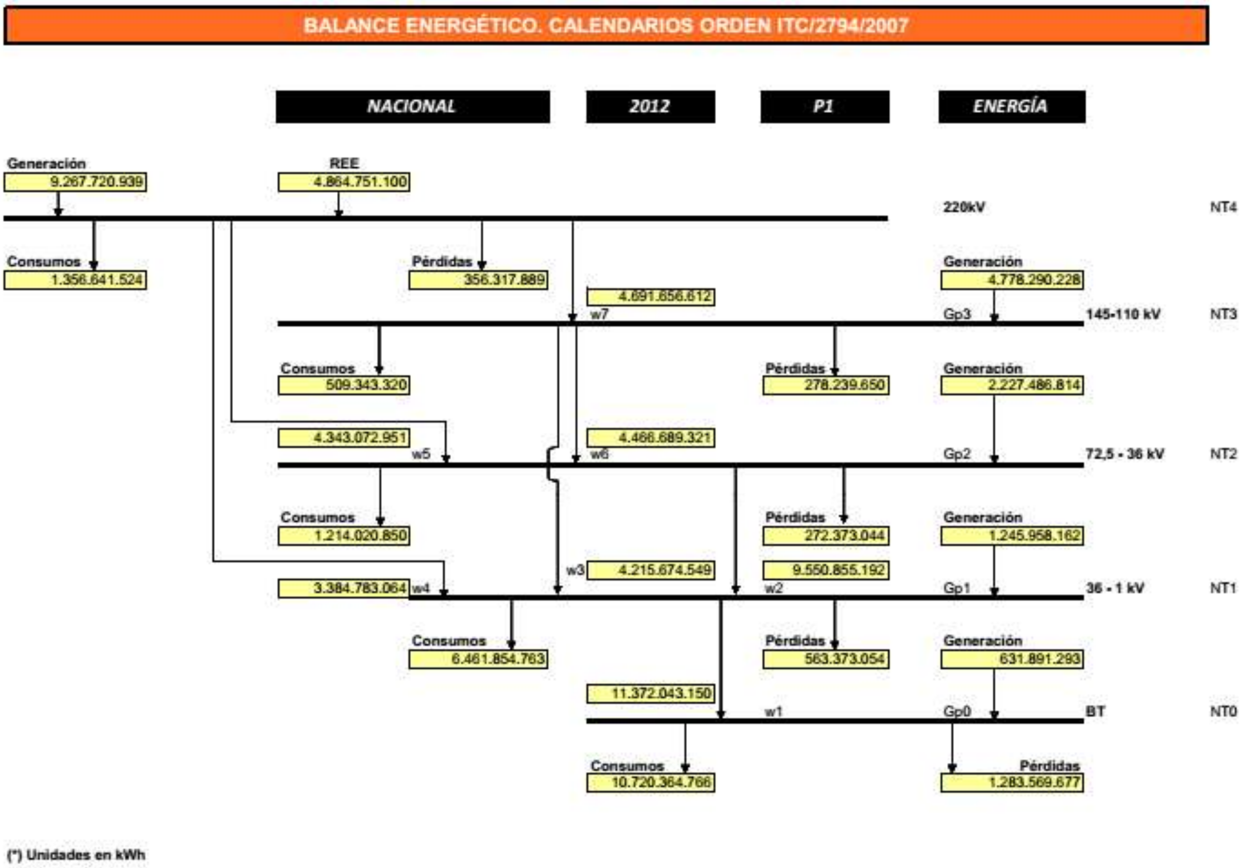

Figure 6 Example of network topology for one representative period P1
(CNMC 2014)

The Spanish regulator differentiates types of days during the year. Table 2 shows the different types of days in one year.

	Description
Type A	Monday to Friday (except holiday) in high season with morning and evening peak.
Type A1	Monday to Friday (except holiday) in high season with morning peak.
Type B	Monday to Friday (except holiday) in mid-season with morning peak.
Type B1	Monday to Friday (except holiday) in mid-season with evening peak.
Type C	Monday to Friday (except holiday) in low season (except August).
Type D	Saturdays, Sundays, holiday and August.

Table 2 Description of types of days

Each period considers an amount of hours for each type of day. Table 3 shows the amount of hours of each type of day depending on each period of time (P1-P6).

			Hours			
Period	**Type A**	**Type A1**	**Type B**	**Type B1**	**Type C**	**Type D**
1	6	8	0	0	0	0
2	10	8	0	0	0	0
3	0	0	6	6	0	0
4	0	0	10	10	0	0
5	0	0	0	0	16	0
6	8	8	8	8	8	24

Table 3 Number of hours depending on type of period

Table 4 shows the number of days of each type of day.

Period	Number of days in 2012
Type A	64
Type A1	32
Type B	31
Type B1	44
Type C	67
Type D	131

Table 4 Number of days depending on type of period in 2012

With the information above, the total number of hours per period is calculated and shown in Table 5.

Period	Total hours
1	694
2	896
3	450
4	750
5	1072
6	5048

Table 5 Total number of hours of each period

With the previous information, the conversion from energy to power units is done, dividing energy by the duration of the period. It is important to note that the aggregated data is given in kWh and the input data of power flows to the ROM model should be given in per unit taking into account the base power used by the ROM model (100 MW).

As illustration of one representative period P1, Table 6 shows the generation, demand and losses units by voltage level. Red Electrica de España (REE) is the system operator who operates the national power transmission system. In this Table, the power assigned to REE is coming from the transmission network (400kV).

Period P1					
Voltage level	**Generation (pu)**	**REE (pu)**	**Demand(pu)**	**Losses (pu)**	**Balance**
220 kV	145	76	21	5,5	194
132 kV	75	-	8	4,3	62,3
60 kV	35	-	19	4,2	11,5
20 kV	19	-	101	8,8	90,3
LV	10	-	168	20	177,6
Total	**284**	**76**	**317**	**43**	**0**

Table 6 Example of aggregated values for one representative period

In order to represent the distribution network in the ROM model a representation of the equivalent system is proposed in Figure 7. This equivalent network scheme is radial and power flows go from the high voltage (400kV) to low voltage levels.

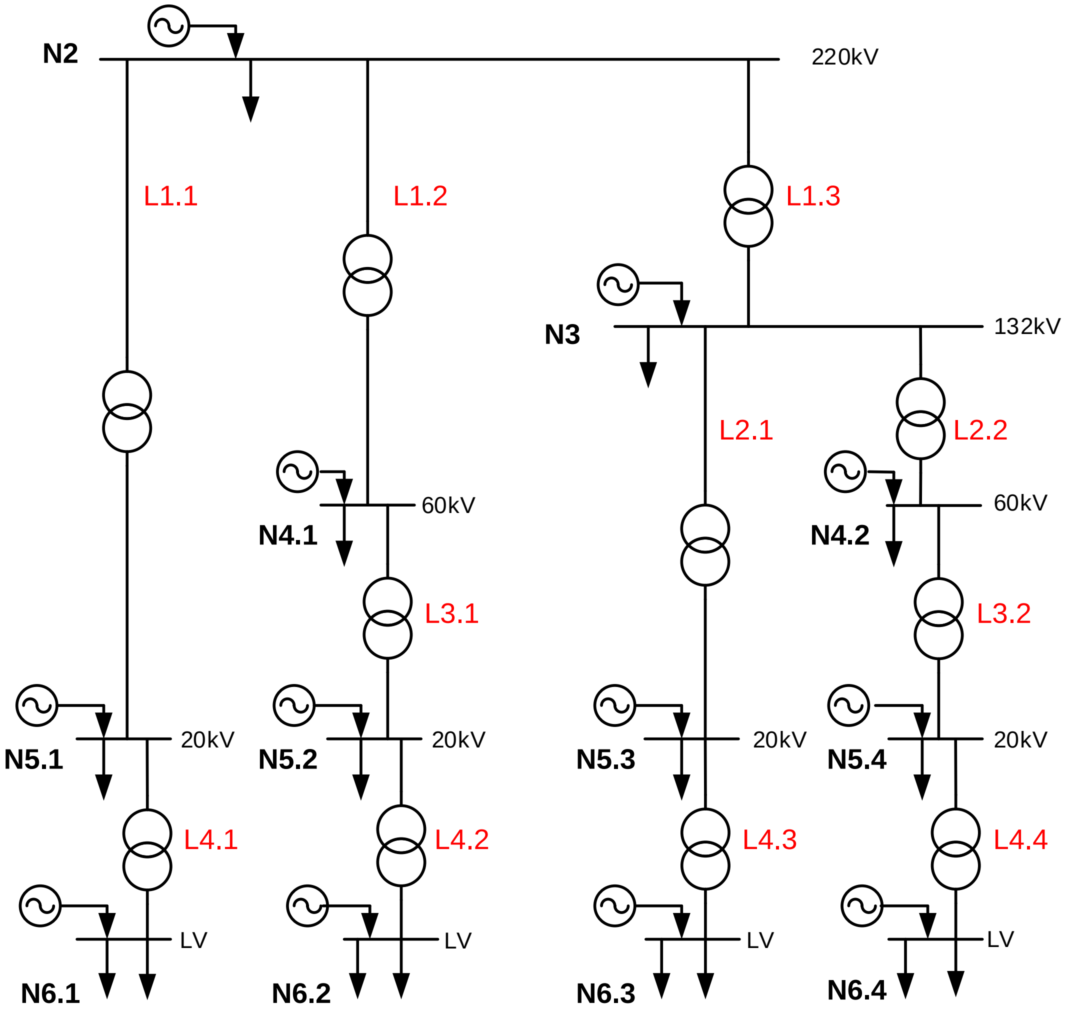

Figure 7 Network topology included in the ROM model

The reported aggregated values for demand and generation units per voltage levels are disaggregated per each node in the previous distribution network scheme. That is needed in order to introduce them as input data in the ROM model.

Demand and generation at each voltage node of the network will be disaggregated in the same proportions as the reported power inflows coming from the upward voltage levels. The results are shown in Table 7.

Period P1								
Voltage level	**Total inflow**	**Inflow 1**	**(%)**	**Inflow 2**	**(%)**	**Inflow 3**	**(%)**	**Total**
220 kV	220,81	221	100%	-	0	-	0	100%
132 kV	73,30	73	100%	-	0%	-	0%	100%
60 kV	137,65	70	51%	68	49%	-	0%	100%
20 kV	267,98	149	56%	66	25%	53	20%	100%
LV	177,68	178	100%	-	0%	-	0%	100%

Table 7 Proportions of power inflows (pu) for one representative period

As it has been said, the proportions of Table 7 are going to be used to distribute generation and demand per nodes at each voltage level (Figure 7).

Initially, the generation and demand at each node are calculated depending on the power inflow proportions, without considering line losses, as shown in Table 8.

Voltage level	Node	Generation (pu)	Weight	Demand (pu)	Weight
220 kV	2	145	100%	21	100%
132 kV	3	75	100%	8	100%
60 kV	4.1	17	49%	9	49%
60 kV	4.2	18	51%	10	51%
20 kV	5.1	4	20%	20	20%
20 kV	5.2	5	27%	28	27%
20 kV	5.3	5	25%	25	25%
20 kV	5.4	5	28%	29	28%
LV	6.1	2	20%	33	20%
LV	6.2	3	27%	46	27%
LV	6.3	2	25%	41	25%
LV	6.4	3	28%	47	28%

Table 8 Proportions of generation and demand nodes for one representative period

The previous generation and demand distribution do not take into account the losses in lines and losses in transformation between voltage levels.

Total losses by voltage level are also given by the report of the Spanish regulator as aggregated values. These losses include power flow losses (ohmic losses) and non-load transformation losses (non-load transformation losses are not the scope of this model, therefore they are not considered in the following).

The equivalent resistance of each of the branches of the previous equivalent scheme is calculated.

To calculate the equivalent resistance of each branch by voltage level two alternative approaches can be followed:

1) Average quadratic losses

The first procedure calculates the resistance of the branch or line i-j at each voltage level by the following formula:

$$R_{ij} = \frac{L_{ij}}{(F_{ij})^2}$$

Where:

R_{ij} = Resistance of line which connect node i with node j;
L_{ij} = Losses in line which connect node i with node j;
F_{ij} = Power flow in line which connect node i with node j;

Equation 1 Voltage level resistance

An average for the six scenarios (time periods P1-P6) is calculated in order to find the most representative resistances.

Voltage level	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Average
220	0,00011	0,00010	0,00012	0,00013	0,00010	0,00013	0,00011
132	0,00080	0,00075	0,00081	0,00089	0,00067	0,00092	0,00081
60	0,00022	0,00019	0,00022	0,00023	0,00017	0,00021	0,00021
20	0,00012	0,00010	0,00011	0,00011	0,00010	0,00013	0,00011
LV	0,00063	0,00050	0,00057	0,00064	0,00052	0,00066	0,00059

Table 9 Voltage level resistances (pu)

2) Losses quadratic function

Energy losses are quadratic to the flow (Figure 8 and Figure 9). Consequently the second procedure consists in approximating the losses by a quadratic function. This approximation is applied in each of the six different scenarios.

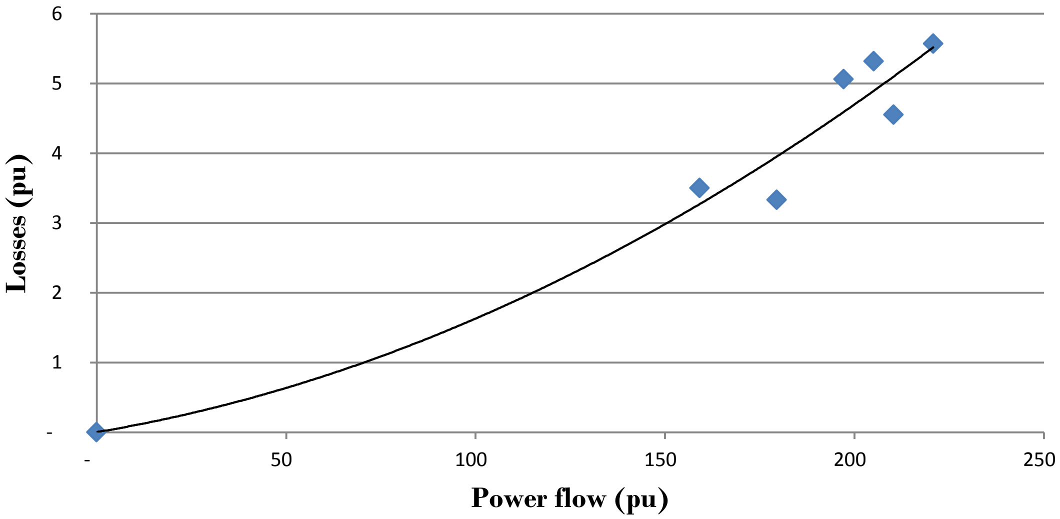

Figure 8 Quadratic relation between losses and power flow for 220 kV

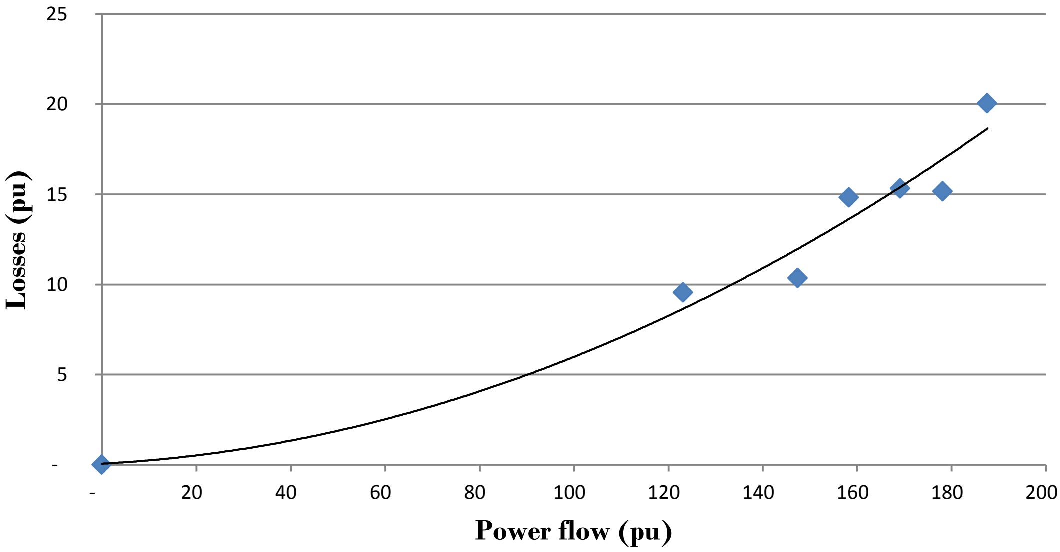

Figure 9 Quadratic relation between losses and power flow for 20 kV

It is expected that the resistance grows with lower voltage levels since there are higher losses in the lower voltage levels.

Comparing both approaches to compute the equivalent resistances it can be checked that both provide similar results (Table 10).

Voltage level	Approximation 1	Approximation 2	Difference (%)
220 kV	1,19E-04	1,19E-04	1%
132 kV	8,13E-04	8,04E-04	1%
60 kV	2,10E-04	2,13E-04	-1%
20 kV	1,15E-04	1,13E-04	1%
LV	5,92E-04	5,84E-04	1%

Table 10 Comparison between voltage level resistance's calculations

The equivalent resistance of each line is calculated taking the corresponding voltage level, the lower voltage level for each line is always assumed.

In Table 11 the calculated line resistances are presented.

Scenario 1	
Line	**Resistance (pu)**
0	1,19E-04
1.1	1,13E-04
1.2	2,13E-04
1.3	8,04E-04
2.1	1,13E-04
2.2	2,13E-04
3.1	1,13E-04
3.2	1,13E-04
4.1	5,84E-04
4.2	5,84E-04
4.3	5,84E-04
4.4	5,84E-04

Table 11 Line's resistances

The final disaggregation of demand and generation per node considering line losses is similar to the disaggregation obtained previously without considering line losses, due to the fact that losses are negligible in comparison to line power flows.

Node 1 and node 2 represent the transmission network (where imports and exports with France and Portugal are also considered). The rest of the nodes of the equivalent system represent the distribution network (Figure 10). Since the distribution network is radial and the use of a DC network representation by the ROM model, the calculation of the equivalent reactance of each line is not needed.

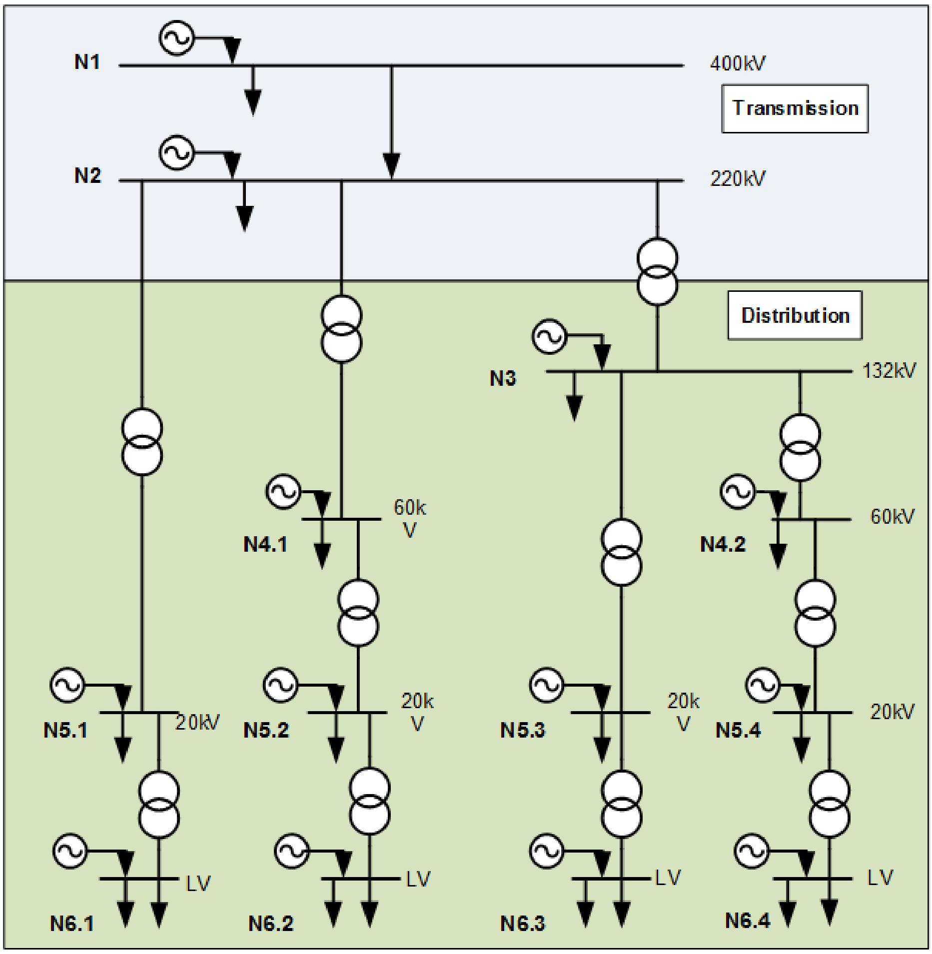

Figure 10 Network topology differentiating transmission from distribution

Conventional thermal units are modeled based on technological characteristics, fuel costs and emissions adapted to 2012 as shown in Table 12. The installed capacity of thermal generation is supposed to be connected at transmission and is optimally dispatched by the ROM model.

Resource	Var. Heat Rate [€/MWh]	O&M Var. Cost [€/MWh]	Fuel cost [€/Mcal]	Emissions [t CO2/MWh]
Nuclear	20	0,1	1	0
Coal	1300	1,01	0,05	0,8

Gas	1461,2	7,09	0,03	0,4

Table 13 Thermal generation characteristics included in the ROM

Hourly renewable generation profiles are included based on actual data for 2012.

Renewable generation is distributed in the network topology based on Table 8 and on Table 14 percentages. The type of renewable resource determines the amount of energy supplied at different voltage levels as shown in Table 14.

Voltage level [kV]	Cogeneration	Solar PV	Solar Thermal	Wind	Hydro
0 ≤ V< 1	1%	36%	0%	1%	1%
1 ≤ kV<36	41%	48%	12%	4%	32%
36 ≤ kV<72,5	31%	12%	9%	12%	33%
72,5 ≤ kV<145	14%	3%	14%	29%	18%
145 ≤ kV ≤ 400	13%	2%	64%	54%	16%

Table 14 Special Regime – Installed capacity 2012
(CNE 2012)

Taking into consideration Table 8 and Table 14 the final distribution of renewable generation in the network topology is based on Table 15.

Node	Cogeneration	Solar PV	Solar Thermal	Biomass	Wind	Hydro
2	13%	2%	64%	33%	54%	33%
3	14%	3%	14%	25%	29%	25%
4.1	15%	6%	5%	13%	6%	13%
4.2	16%	6%	5%	14%	6%	14%
5.1	8%	9%	2%	2%	1%	2%
5.2	11%	13%	3%	3%	1%	3%
5.3	10%	12%	3%	3%	1%	3%
5.4	11%	13%	3%	3%	1%	3%
6.1	0%	7%	0%	0%	0%	0%
6.2	0%	10%	0%	1%	0%	1%
6.3	0%	9%	0%	1%	0%	1%
6.4	0%	10%	0%	1%	0%	1%

Table 15 Distributed generation in network's topology

Demand profiles follow the same reasoning. Annual hourly demand data of 2012 is distributed by nodes in MW's according to Table 8 percentages.

At this point, the input data to be included in the ROM model are:

- Line's resistances
- Renewable generation annual hourly profiles
- Demand annual hourly profiles

In order to check that input data have been calculated and introduced in ROM properly, two main results are supervised once the ROM model is executed :

1) Losses in relation to demand

Percentage of losses in relation to demand is an extremely important parameter to be supervised. This parameter is not a direct output of the ROM model but it can easily be calculated with lines losses (output) and demand (input).

This parameter measures the proportion of losses in the distribution network in relation to the demand.

Comparing this relation with some reference values of distribution networks (approximately 10%) allows evaluating if the results provided by ROM are sound and consistent.

2) Energy Not Supplied (ENS)

ENS stands for energy not supplied and it is an output of the ROM model. This parameter represents the energy that is not supplied in nodes of the grid.

The supervision of this parameter forces the supervision of the maximum line capacities, and the maximum power flows. If ENS is different from zero in one node, it is possible that the power flow at the line that supplies that node has reached its maximum capacity and so not all the energy needed in the node reaches the node, and therefore ENS would exist.

For the proper assessment of other outputs of ROM, in this project it is assumed that it must not exist ENS in any node of the network.

CASE STUDIES

In this section case studies of the project are presented.

In order to answer the main questions under research mentioned in Introduction section, three versions of quadratic losses model are developed (Flexible Cogeneration, Centralized and Decentralized PV).

Additionally initial ROM model ("Single node") is considered for comparison reasons.

Four case studies are developed:

9. Quadratic losses vs. Single node
10. Inflexible Cogeneration vs. Flexible Cogeneration
11. Flexible Cogeneration vs. Flexible Cogeneration in Single node model
12. Centralized vs. Decentralized PV

1 – Quadratic losses vs. Single node

Original Single node model closely resembles the current market outcomes of the Spanish system.

Single node model considers network as a single node by considering line's losses effect null.

By introducing losses calculated in quadratic losses model in the single node model's demand input make these two models comparable.

This simplification has consequences in nodal prices compared to quadratic losses model that approximates losses quadratically to the flow. One of the consequences is that marginal prices remain equal for the different nodes.

Average marginal nodal prices weighted by demand are a result of this case study. Costs of demand and generation remunerations are going to be calculated and analyzed.

The following results are compared for the two cases:

1) Demand costs are calculated by multiplying average marginal nodal prices weighted by demand by the nodal demand.
2) Generation remunerations are calculated by multiplying average marginal nodal prices weighted by demand by the nodal generation units.

This comparison pretends to enhance the importance of a better and updated grid modulation in order to reflect more appropriated nodal prices and consequently demand costs and generation remuneration.

2 – Inflexible Cogeneration vs. Flexible Cogeneration

Cogeneration technologies and efficient District Heating and Cooling (DHC) can potentially support an integrated energy system by regulating electricity and thermal energy while delivering enhanced energy efficiency. This regulation is done through changes in the operating loads, thermal storage and heat pumps.

It is wanted to enhance the need to create a long-term stable market environment that incentivizes energy efficiency as a critical factor for the uptake of these technologies, as well as strategic planning for energy infrastructure to optimize the use of local energy sources.

Changes in processes are very expensive investments. Actual support mechanisms such as feed-in-tariffs do not incentive cogeneration flexibility.

With this case study an increment of cogeneration revenues and a reduction of thermal costs and emissions are attempted in order to optimize the system.

Two cases are compared (both with quadratic losses approximation). Firstly inflexible cogeneration, with initial CHP loads. Secondly flexible cogeneration with the possibility to change CHP loads from one hour to another up to 25%.

In order to simulate flexible cogeneration three steps are needed. Initial CHP in ROM model result in marginal nodal prices which are introduced along with initial CHP in an auxiliary optimization program that determines which are the best hours to operate CHP. CHP generation can range up to 25% from one hour to another.

Finally, introducing the optimized CHP operation results in ROM model flexibility is reached.

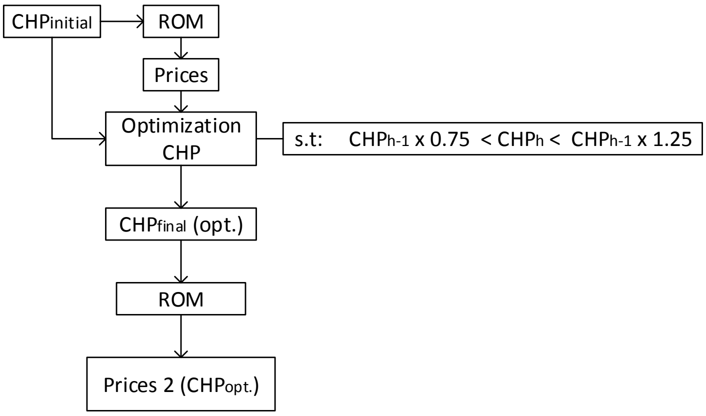

Figure 11 Scheme of flexibility reasoning

With efficient price signals, CHPs (combined heat and power units) can contribute to balance variable renewable sources.

What is attempted with flexible cogeneration model is that when price signals are very high (surplus of renewable energy resources) a decrease in CHPs and in hydro pump consumptions occur.

3 – Flexible Cogeneration vs. Flexible Cogeneration in Single node model

The system operator models the network as centralized network, without considering distribution losses. However, in reality this losses need to be supplied.

This case study wants to study the effects of flexible cogeneration comparing quadratic losses approximation with single node model that considers network as centralized network (losses calculated in quadratic losses model are considered in demand input in order to make these two models comparable).

Again, since single node model considers line losses effect null, the marginal prices remain equal for all nodes, and flexible cogeneration has the possibility to change CHP loads from one hour to another up to 25% in both models.

The comparison between these two models pretends to show that marginal nodal prices and CHPs remuneration are higher in quadratic losses model since modeled losses are closer to real losses.

4 – Centralized vs. Decentralized PV

Over the past few years, many PV power plants have been built with centralized architectures, while demand for increasingly more powerful central inverters for these projects has grown.

There is no choice that results in an optimal PV plant, since it depends on the client's individual needs.

Lower losses and lower network costs are advantages in decentralized PV power plants, but in the other hand, the investment in a centralized PV power plant is approximately 30% cheaper than a decentralized PV power plant investment (MIT 2015).

In this case study the comparison between these two options is checked, if the higher investment costs in decentralized PV power plants are compensated with savings in losses.

In order to observe in a more significant way this comparison PV power generation is doubled with respect to initial installed capacity of 2012 for Spanish system, which was 4500 MW.

In centralized PV power plants case all PV power generation is included in node 2 (Transmission level in Figure 10) and in decentralized PV power plants case all PV power generation is distributed in lower voltage (Node 6.1, 6.2, 6.3, and 6.4 in Figure 10) using proportions of Table 15.

Losses based on demand, thermal costs, emissions, weighted average marginal price and nodal prices effects are outputs under analysis.

RESULTS

In this section results of the case studies are presented and discussed.

Case studies:

1. Quadratic losses vs. Single node
2. Inflexible Cogeneration vs. Flexible Cogeneration
3. Flexible Cogeneration vs. Flexible Cogeneration in Single node model
4. Centralized vs. Decentralized PV

1 – Quadratic losses vs. Single node

Average marginal nodal prices weighted by demand at each node, market costs of demand and generation remunerations are compared in order to observe the effects of different losses approximation. Figure 12 shows marginal prices in network topology for quadratic losses model. The marginal price in single node model is 46.4 €/MWh and it remains equal for the different nodes of network topology.

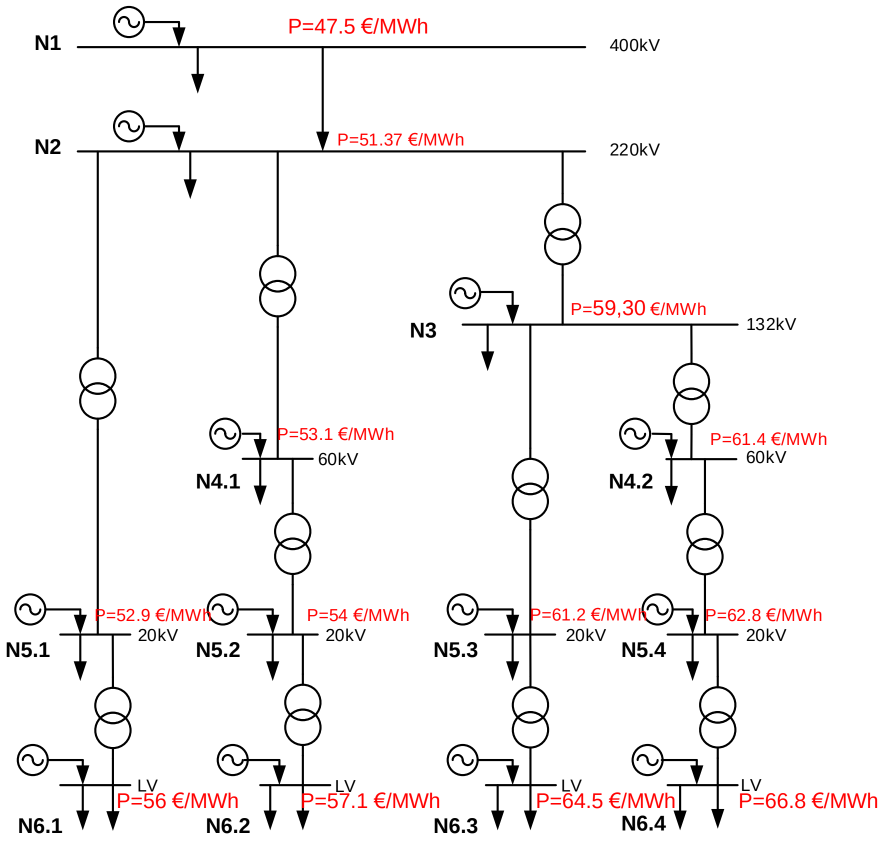

Figure 12 Average marginal nodal prices weighted by demand in network topology

Table 16 compares average marginal nodal prices weighted by demand at each node with quadratic losses model vs single node model considering quadratic losses in demand.

Node	Difference (%)
1	±2
2	±10
3	±22
4.1	±13
4.2	±24
5.1	±12
5.2	±14
5.3	±24
5.4	±26
6.1	±17
6.2	±19
6.3	±28
6.4	±31

Table 16 Comparison of average marginal nodal prices weighted by demand

In the single node model average marginal nodal prices remain equal for all nodes since line's losses effect are considered null.

As shown in Table 16 an increment of almost 30% is shown from transmission voltage level (Node 1) to low voltage level (Node 6).

The difference between these prices can be justified by the fact that for an extra MW in quadratic losses model demand must pay all the losses collected in the way from transmission to the corresponding distribution.

By using marginal prices apart from losses costs, part of the network costs can be recovered. In contrast, the price signals in single node model does not reflect either losses costs or network costs.

Table 17 shows demand costs for both models.

The difference between demand costs in quadratic losses model and single node model reflects losses costs and part of network total costs in a single node representation.

With single node model, consumers do not get rid of paying these costs, instead, costs are reflected separately of single node model in consumer's bill.

Node	Quadratic losses model (M€)	Single node model (M€)	Difference (M€)
1	277	246	31
2	1.258	1.137	121
3	561	442	119
4.1	438	387	50
4.2	523	400	123
5.1	624	556	68
5.2	1.019	890	130
5.3	1.041	802	239
5.4	1.223	918	305
6.1	1.038	858	181
6.2	1.693	1.373	320
6.3	1.724	1.237	487
6.4	2.042	1.416	627
Total	13.462	10.661	**2.801**

Table 17 Demand costs

Table 18 represents remuneration of generation units for both models.

Node	Quadratic losses model (M€)	Single node model (M€)	Difference (%)
1	8.543	6.581	23
2	1.758	1.520	14
3	1.160	887	24
4.1	466	407	13
4.2	541	410	24
5.1	172	152	11
5.2	271	236	13
5.3	269	207	23
5.4	317	238	25
6.1	29	24	18
6.2	46	37	19
6.3	46	33	28
6.4	54	38	31
Total	**13.673**	**10.770**	

Table 18 Generation units remuneration

As expected generation units of quadratic losses model have more revenues than in single node model.

Higher remuneration for generation units is in transmission level (Node 1) since thermal and large hydro are included in this voltage level.

2 – Inflexible Cogeneration vs. Flexible Cogeneration

The impact of making flexible cogeneration is analyzed firstly discussing differences in economical dispatch with inflexible cogeneration.

Secondly, average marginal nodal prices weighted by demand are compared.

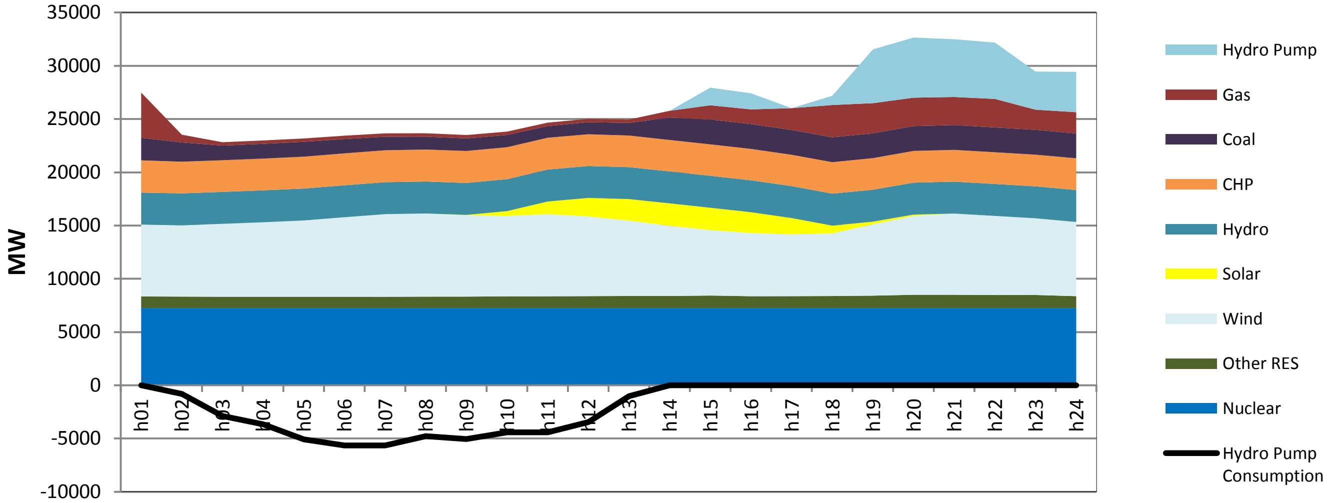

Figure 13 Inflexible cogeneration

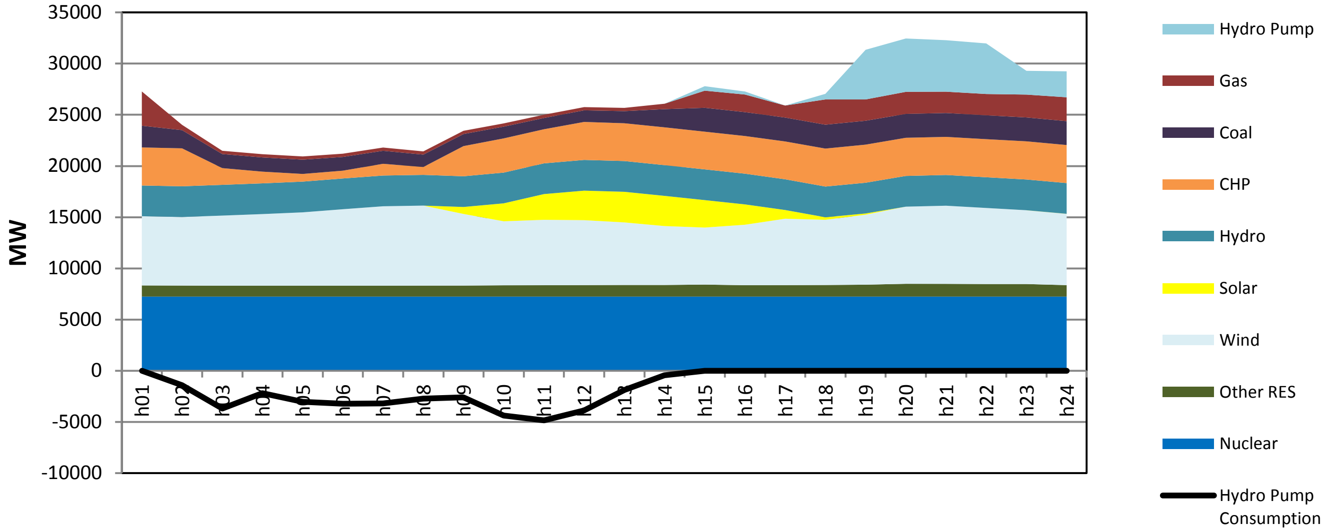

Figure 14 Flexible cogeneration

Figure 13 and Figure 14 differences show a decrement of CHPs generation together with a reduction of hydro pump consumption, from hour 3 to 8 in comparison with the case of inflexible CHPs.

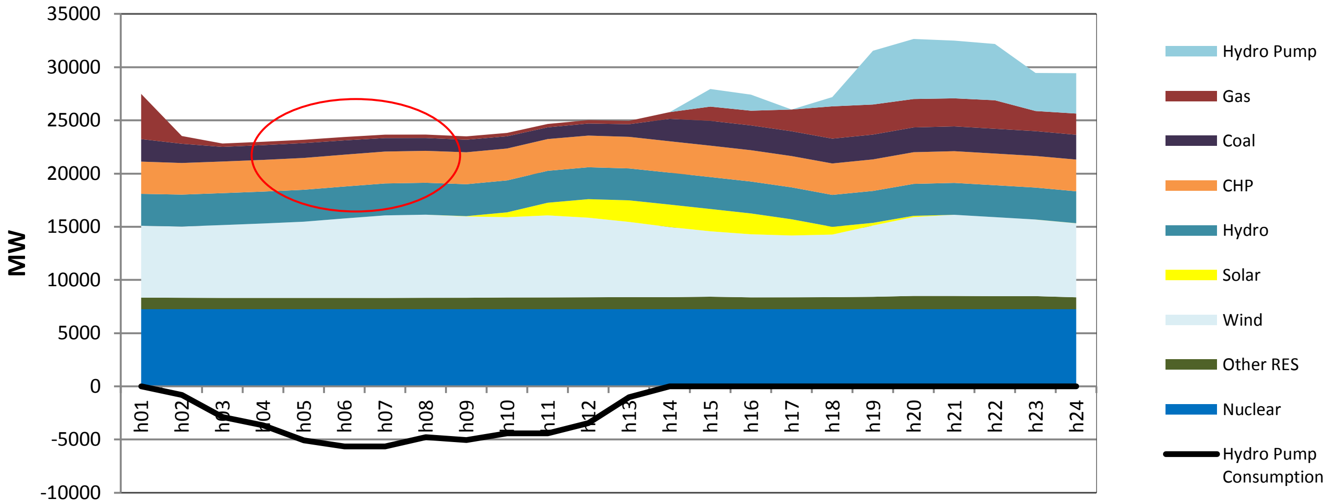

Figure 15 Inflexible cogeneration

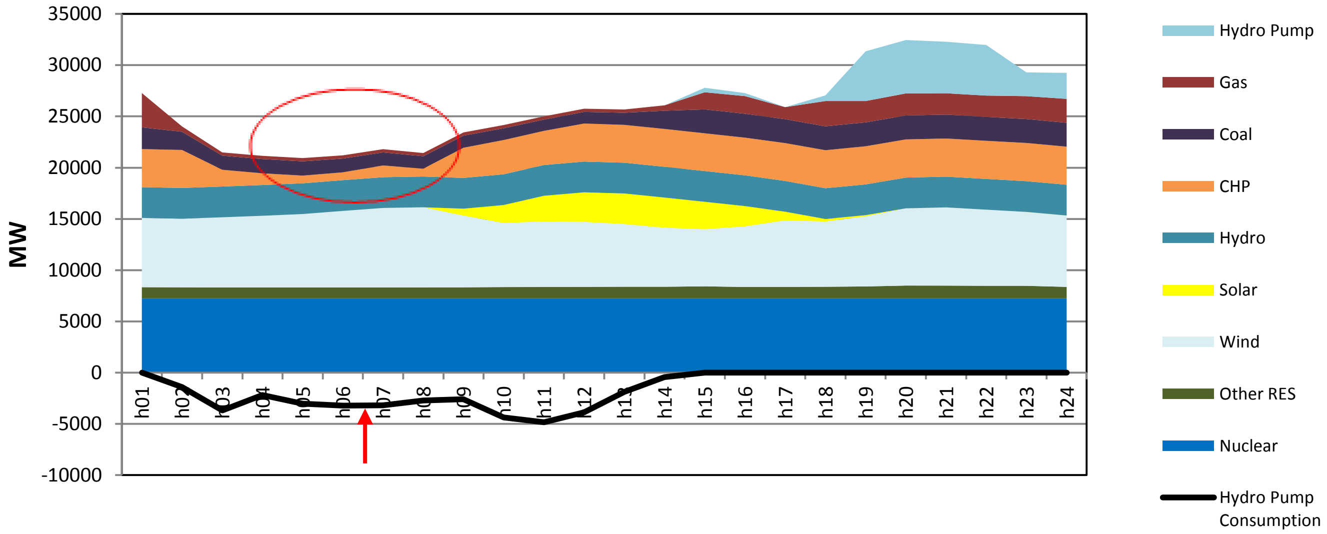

Figure 16 Flexible cogeneration

Flexible CHP can impact the economic dispatch and potentially reduce thermal costs by around 2%. However, the additional income from flexibility needs to be compared with the costs of providing flexibility which has not been considered in this analysis.

Table 19 compares average marginal nodal prices weighted by demand at each node following network topology for both cases with inflexible cogeneration and flexible cogeneration models.

Node	Flexible CHP (€/MWh)	Inflexible CHP (€/MWh)	Difference (%)
1	47.9	47.5	0,82
2	51.6	51.4	0,37
3	59.4	59.3	0,09
4.1	53.1	53.0	0,12
4.2	61.4	61.4	-0,08
5.1	52.9	52.9	-0,10
5.2	53.9	54.0	-0,13
5.3	61.0	61.2	-0,34
5.4	62.6	62.8	-0,39
6.1	55.7	56.0	-0,55
6.2	56.7	57.1	-0,59
6.3	64.0	64.5	-0,84
6.4	66.2	66.8	-0,91

Table 19 Average marginal nodal prices weighted by demand

It is observed that marginal nodal prices with flexible CHP are higher in transmission network compared to distribution network as there are few CHPs units connected at the transmission network. In addition, on average flexible CHPs reduce marginal prices, the effect is higher at nodes where more CHPs are connected

3 – Flexible Cogeneration vs. Flexible Cogeneration in Single node model

Flexible cogeneration results are presented in the previous case study results (Table 19).

Single node model with flexible CHP resulted in a marginal nodal price of 47 €/MWh.

Table 20 compares the average marginal nodal prices weighted by demand following network topology for both models: Quadratic losses (locational) and single node.

Node	Difference (%)
1	2
2	9
3	21
4.1	11
4.2	23
5.1	11
5.2	13
5.3	23
5.4	25

6.1	16
6.2	17
6.3	27
6.4	29

Table 20 Comparison of average marginal nodal prices weighted by demand

At this point, to evaluate the impact of quadratic losses model with flexibility the incomes of CHPs are compared with single node model in Figure 17.

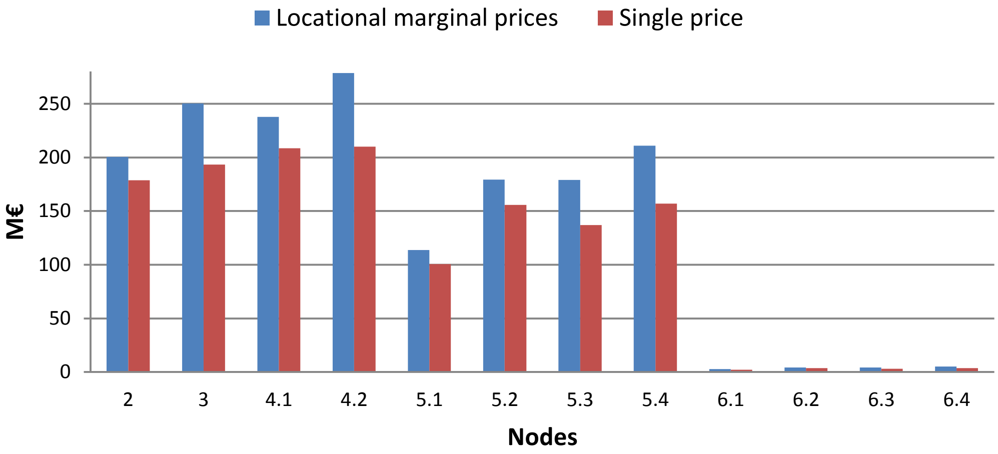

Figure 17 CHPs remuneration

Market income of CHPs based on locational marginal prices increases on average by 23% in comparison with single node price, providing additional incentives to be flexible.

4 – Centralized vs. Decentralized PV

First, in order to evaluate the differences between centralized and decentralized PV, where Spanish system with initial PV capacity of 4500 MW was doubled for both cases, average of marginal nodal prices weighted by demand are compared in Table 21.

Node	Centralized PV (€/MWh)	Decentralized PV (€/MWh)	Difference (%)
1	44.8	43.8	2
2	50.1	49.5	1
3	57.9	56.9	2
4.1	51.7	51.2	1
4.2	59.9	58.8	2
5.1	51.4	50.9	1
5.2	52.5	51.9	1

5.3	59.5	58.4	2
5.4	61.1	59.9	2
6.1	54.3	53.4	2
6.2	55.3	54.5	1
6.3	62.6	61.2	2
6.4	64.5	63.1	2

Table 21 Average marginal nodal prices weighted by demand

Secondly, the benefits of decentralized over centralized PV are shown in Table 22.

Benefits of decentralized over centralized PV	[%]	[M€]	[€/MW of installed PV]
Losses	-11	-144	-32
Thermal costs	-3	-123	-27
Emissions	-2	-7	-2
Demand payments	-2	-225	-50
Solar income (new capacity)	+11	+41	+9

Table 22 Centralized vs. Decentralized PV – System impacts

Decentralized PV, in comparison with centralized PV, reduces losses, thermal costs, emissions and market demand payments at nodal prices. The higher effect is on electricity losses which significantly reduces network losses.

Market income for solar PV is higher for decentralized PV as they are located at low voltage levels.

CONCLUSIONS

With the methodology followed the objective of introducing a schematic representation of the distribution network in the ROM model was achieved.

The major obstacles in the methodology section were: the calculus of inflows proportions from reported aggregated data; the calculus of voltage level resistances and their distribution on network topology.

At this point, the main questions under research introduced at the beginning of this document are answered and finally additional remarks are added.

- **What is the impact of distribution energy losses on locational marginal prices at different voltage levels?**

  Considering the system as a centralized network despises distribution losses. Even if these losses are considered with linear coefficients, which is the methodology used by the system operator in Spain, the approximation leads to inadequate distribution losses accounting.

  Including distribution of energy losses in ROM model, by lines' resistance as input data, demonstrated that locational marginal prices grow with lower voltage levels quadratically.

- **How do locational marginal prices at voltage levels impact on demand payments and generation incomes?**

  Demand payments and generation incomes depend on the location of demand and generation units in the different nodes of the grid times in the hourly locational marginal prices.

  Since locational marginal prices grow with lower voltage level so do the demand payments and generation incomes.

- **How centralized vs. decentralized resources impact the system costs by accounting for distribution losses?**

  In results of centralized vs. decentralized PV case study, the major impacts observed were in the system costs and not in locational marginal prices.

  Decentralized resources have the disadvantage of higher investments in installations, but in the other hand they present benefits in system costs such as reductions in: losses, thermal costs, emissions and at the end on lower market demand payments.

It is important to compare decentralized resources installations investments with benefits obtained from the system in order to make the right decision.

- **How does the economic dispatch of flexible DERs change with and without considering the effect of distribution losses?**

  In flexible cogeneration vs. inflexible cogeneration case study results, it was observed that flexible CHPs impact the economic dispatch and reduce thermal costs.

  Considering the effect of distribution losses in the system leads to an increment in incomes of DERs based on locational marginal prices in comparison with single node price.

With the presented case studies results and the increment of distributed resources on the energy system make the traditional centralized system representation in a single node inappropriate and therefore a new approach in the grid is needed.

A simplified model can capture relevant impact of distribution losses on locational prices at voltage levels.

Considering distribution losses in the system approach has a significant impact on nodal prices and consequently in generation market income, demand market payments and in the efficiency of the electricity system.

For generation units locational marginal prices can provide locational incentives for new generation units (e.g. new PV) and flexibility incentives (e.g. CHP).

Distribution locational marginal prices can have important impacts on the operation and investment decisions of other flexible resources such as electric vehicles, storage and demand response. Other relevant price signals such as the impact of network congestions on nodal prices are next steps for the development of the proposed methodology

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ATTACHMENTS

In this section attachments of the project are included.

Firstly, the reported aggregated data (six periods) by Spanish Energy Regulator (Comisión Nacional de Mercados y Competencia – CNMC) is shown.

Period P1					
Voltage level	**Generation (pu)**	**REE(pu)**	**Demand(pu)**	**Losses (pu)**	**Balance**
220 kV	145	76	21	5,5	194
132 kV	75	-	8	4,3	62,3
60 kV	35	-	19	4,2	11,5
20 kV	19	-	101	8,8	90,3
LV	10	-	168	20	177,6
Total	**284**	**76**	**317**	**43**	**0**

Table 23 Aggregated values for P1

Period P2					
Voltage level	**Generation (pu)**	**REE (pu)**	**Demand (pu)**	**Losses (pu)**	**Balance**
220	140	70	23	4,55	182
132	71	-	9	3,61	59
60	34	-	19	3,41	12
20	17	-	91	6,52	80
LV	5	-	163	15,17	173
Total	**268**	**70**	**305**	**33**	**0**

Table 24 Aggregated values for P2

Period P3					
Voltage level	**Generation (pu)**	**REE (pu)**	**Demand (pu)**	**Losses (pu)**	**Balance**
220	136	69	24	5,32	176
132	70	-	10	3,41	57
60	37	-	19	3,58	14
20	19	-	95	6,83	83
LV	6	-	154	15,33	163
Total	**268**	**69**	**302**	**34**	**0**

Table 25 Aggregated values for P3

Period P4					
Voltage level	**Generation (pu)**	**REE (pu)**	**Demand (pu)**	**Losses (pu)**	**Balance**
220	132	65	26	5,06	166
132	66	-	10	3,38	53
60	36	-	19	3,29	14
20	19	-	93	6,24	81
LV	6	-	143	14,84	152
Total	**260**	**65**	**292**	**33**	**0**

Table 26 Aggregated values for P4

Period P5					
Voltage level	**Generation (pu)**	**REE (pu)**	**Demand (pu)**	**Losses (pu)**	**Balance**
220	120	60	25	3,33	151
132	64	-	10	2,08	52
60	34	-	19	2,10	13
20	19	-	90	4,69	75
LV	7	-	137	10,35	141
Total	**244**	**60**	**281**	**23**	**0**

Table 27 Aggregated values for P5

Period P6					
Voltage level	**Generation (pu)**	**REE (pu)**	**Demand (pu)**	**Losses (pu)**	**Balance**
220	109	50	27	3,50	129
132	57	-	10	2,15	45
60	29	-	18	1,95	9
20	13	-	71	4,57	62
LV	3	-	114	9,56	120
Total	**212**	**50**	**240**	**22**	**0**

Table 28 Aggregated values for P6

Finally, the quadratic relations between losses and power flow obtained in methodology section for all voltage levels are shown.

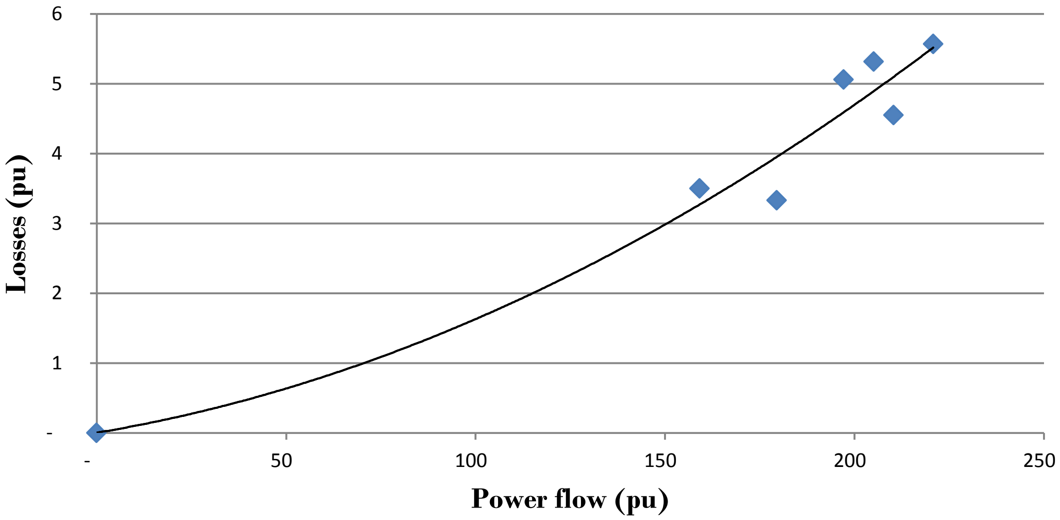

Figure 18 Quadratic relation between losses and power flow for 220 kV

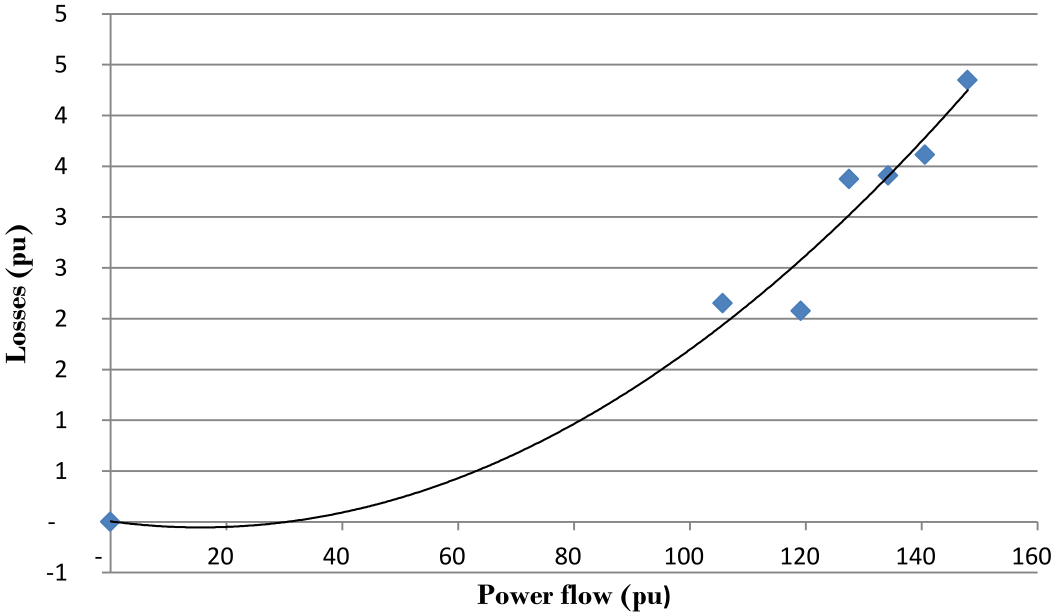

Figure 19 Quadratic relation between losses and power flow for 132 kV

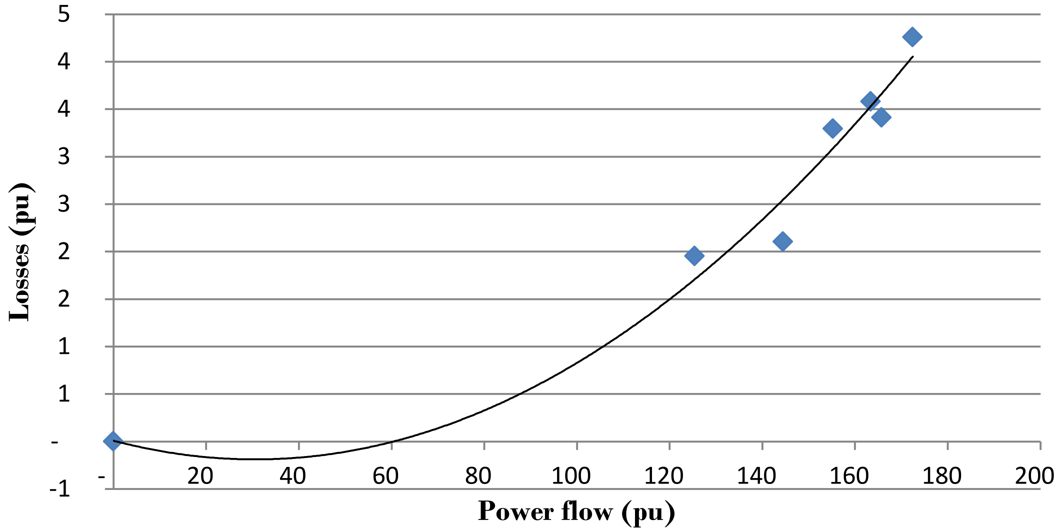

Figure 20 Quadratic relation between losses and power flow for 60 kV

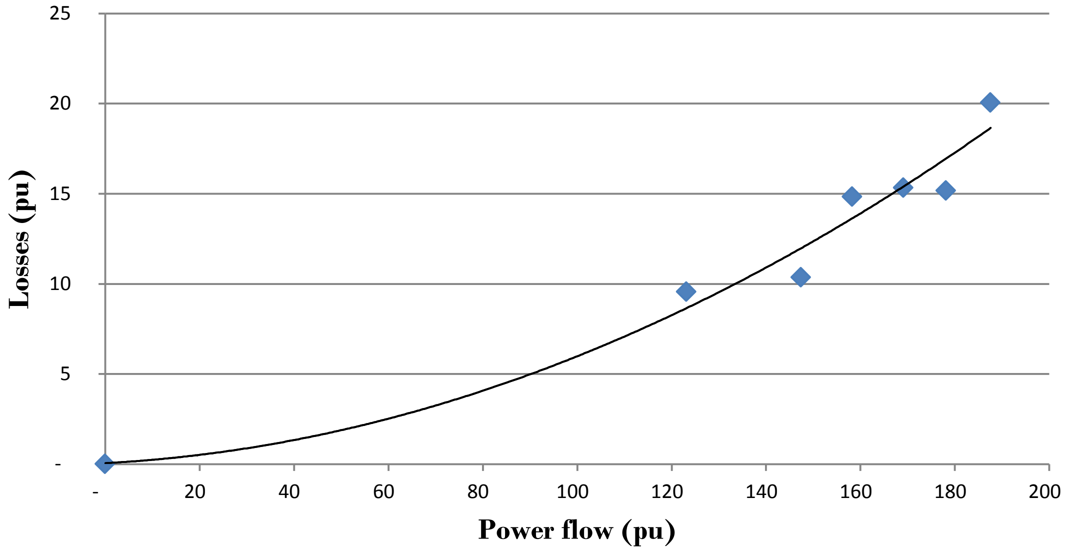

Figure 21 Quadratic relation between losses and power flow for 20 kV

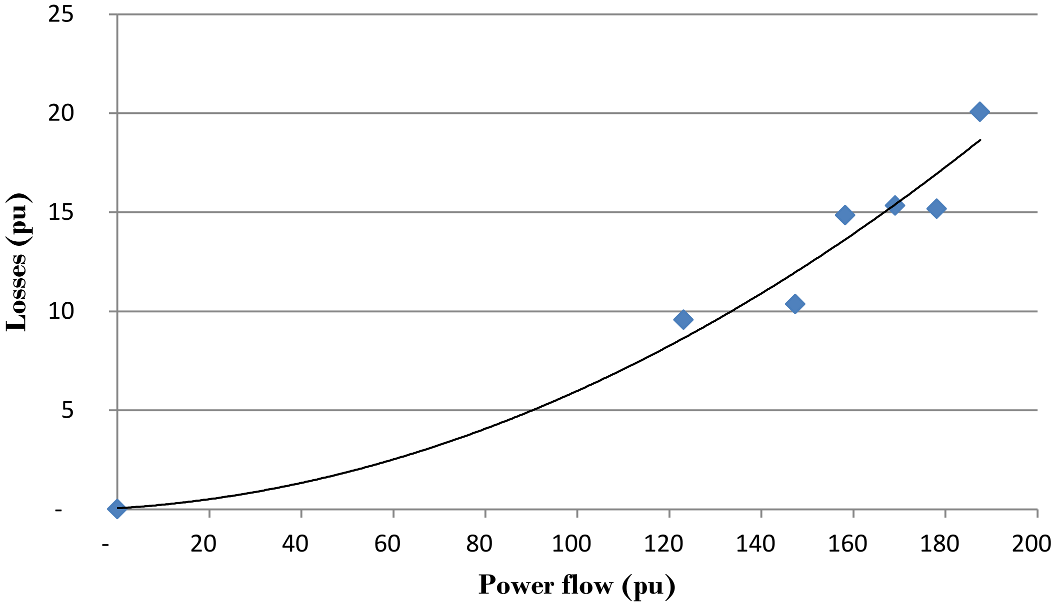

Figure 22 Quadratic relation between losses and power flow for 20 kV