ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

ESPECIALIDAD ELÉCTRICA

PROYECTO FIN DE GRADO

# *Control of distribution network with the integration of dispersed energy storage systems with Multi-Agent system approach:*

## DEVELOPMENT OF FIRST AND SECOND LEVELS OF CONTROL OF HIERARCHICAL APPROACH.

Madrid, July 2014

GONZALO EGEA DE LA MATA

ASISSTANT: MARYAM BAHRAMPINAH

DIRECTOR: RACHID CHERKAOUI

## AUTORIZACIÓN PARA LA DIGITALIZACIÓN, DEPÓSITO Y DIVULGACIÓN EN ACCESO *ABIERTO* ( *RESTRINGIDO*) DE DOCUMENTACIÓN

### *1º. Declaración de la autoría y acreditación de la misma.*

El autor D. Gonzalo Egea de la Mata, como estudiante de Grado en Ingeniería Electromecánica de la UNIVERSIDAD PONTIFICIA COMILLAS (COMILLAS), **DECLARA**

que es el titular de los derechos de propiedad intelectual, objeto de la presente cesión, en relación con el Proyecto Fin de Grado titulado Control of distribution network with the integration of energy storage systems with Multi-Agent systems approach: Development of first and second levels of hierarchical approach[1], que ésta es una obra original, y que ostenta la condición de autor en el sentido que otorga la Ley de Propiedad Intelectual como titular único o cotitular de la obra.

En caso de ser cotitular, el autor (firmante) declara asimismo que cuenta con el consentimiento de los restantes titulares para hacer la presente cesión. En caso de previa cesión a terceros de derechos de explotación de la obra, el autor declara que tiene la oportuna autorización de dichos titulares de derechos a los fines de esta cesión o bien que retiene la facultad de ceder estos derechos en la forma prevista en la presente cesión y así lo acredita.

### *2º. Objeto y fines de la cesión.*

Con el fin de dar la máxima difusión a la obra citada a través del Repositorio institucional de la Universidad y hacer posible su utilización de *forma libre y gratuita* ( *con las limitaciones que más adelante se detallan*) por todos los usuarios del repositorio y del portal e-ciencia, el autor **CEDE** a la Universidad Pontificia Comillas de forma gratuita y no exclusiva, por el máximo plazo legal y con ámbito universal, los derechos de digitalización, de archivo, de reproducción, de distribución, de comunicación pública, incluido el derecho de puesta a disposición electrónica, tal y como se

---

[1] Especificar si es una tesis doctoral, proyecto fin de carrera, proyecto fin de Máster o cualquier otro trabajo que deba ser objeto de evaluación académica

describen en la Ley de Propiedad Intelectual. El derecho de transformación se cede a los únicos efectos de lo dispuesto en la letra (a) del apartado siguiente.

***3º. Condiciones de la cesión.***

Sin perjuicio de la titularidad de la obra, que sigue correspondiendo a su autor, la cesión de derechos contemplada en esta licencia, el repositorio institucional podrá:

(a) Transformarla para adaptarla a cualquier tecnología susceptible de incorporarla a internet; realizar adaptaciones para hacer posible la utilización de la obra en formatos electrónicos, así como incorporar metadatos para realizar el registro de la obra e incorporar “marcas de agua” o cualquier otro sistema de seguridad o de protección.

(b) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato. .

(c) Comunicarla y ponerla a disposición del público a través de un archivo abierto institucional, accesible de modo libre y gratuito a través de internet.[2]

(d) Distribuir copias electrónicas de la obra a los usuarios en un soporte digital. [3]

***4º. Derechos del autor.***

---

[2] En el supuesto de que el autor opte por el acceso restringido, este apartado quedaría redactado en los siguientes términos:

(c) Comunicarla y ponerla a disposición del público a través de un archivo institucional, accesible de modo restringido, en los términos previstos en el Reglamento del Repositorio Institucional

[3] En el supuesto de que el autor opte por el acceso restringido, este apartado quedaría eliminado.

El autor, en tanto que titular de una obra que cede con carácter no exclusivo a la Universidad por medio de su registro en el Repositorio Institucional tiene derecho a:

a) A que la Universidad identifique claramente su nombre como el autor o propietario de los derechos del documento.

b) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.

c) Solicitar la retirada de la obra del repositorio por causa justificada. A tal fin deberá ponerse en contacto con el vicerrector/a de investigación (curiarte@rec.upcomillas.es).

d) Autorizar expresamente a COMILLAS para, en su caso, realizar los trámites necesarios para la obtención del ISBN.

d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

***5º. Deberes del autor.***

El autor se compromete a:

a) Garantizar que el compromiso que adquiere mediante el presente escrito no infringe ningún derecho de terceros, ya sean de propiedad industrial, intelectual o cualquier otro.

b) Garantizar que el contenido de las obras no atenta contra los derechos al honor, a la intimidad y a la imagen de terceros.

c) Asumir toda reclamación o responsabilidad, incluyendo las indemnizaciones por daños, que pudieran ejercitarse contra la Universidad por terceros que vieran infringidos sus derechos e intereses a causa de la cesión.

d) Asumir la responsabilidad en el caso de que las instituciones fueran condenadas por infracción de derechos derivada de las obras objeto de la cesión.

***6º. Fines y funcionamiento del Repositorio Institucional.***

La obra se pondrá a disposición de los usuarios para que hagan de ella un uso justo y respetuoso con los derechos del autor, según lo permitido por la legislación aplicable, y con fines de estudio, investigación, o cualquier otro fin lícito. Con dicha finalidad, la Universidad asume los siguientes deberes y se reserva las siguientes facultades:

a) Deberes del repositorio Institucional:

- La Universidad informará a los usuarios del archivo sobre los usos permitidos, y no garantiza ni asume responsabilidad alguna por otras formas en que los usuarios hagan un uso posterior de las obras no conforme con la legislación vigente. El uso posterior, más allá de la copia privada, requerirá que se cite la fuente y se reconozca la autoría, que no se obtenga beneficio comercial, y que no se realicen obras derivadas.

- La Universidad no revisará el contenido de las obras, que en todo caso permanecerá bajo la responsabilidad exclusiva del autor y no estará obligada a ejercitar acciones legales en nombre del autor en el supuesto de infracciones a derechos de propiedad intelectual derivados del depósito y archivo de las obras. El autor renuncia a cualquier reclamación frente a la Universidad por las formas no ajustadas a la legislación vigente en que los usuarios hagan uso de las obras.

- La Universidad adoptará las medidas necesarias para la preservación de la obra en un futuro.

b) Derechos que se reserva el Repositorio institucional respecto de las obras en él registradas:

- retirar la obra, previa notificación al autor, en supuestos suficientemente justificados, o en caso de reclamaciones de terceros.

Madrid, a 15 de Julio de 2014

**ACEPTA**

Fdo……………………………………………………………

Autorizada la entrega del proyecto al alumno:

Gonzalo Egea de la Mata

EL DIRECTOR DEL PROYECTOR

Rachid Cherkaoui

Fdo: Fecha: 03/07/2014

Vº Bº DEL COORDINADOR DE PROYECTOS

Fernando de Cuadra

Fdo: Fecha: / /

# ABSTRACT

Electric power systems are increasingly facing greater challenges from changing regulations, evolutions in demand requirements and the incorporation of distributed generation (DG) from renewable energy sources (RES). These changes have shown a clear incompatibility with traditional operating control methods due to the lack of controllability at the low voltage (LV) level. For such problem, the most promising solution seems to be to indirectly control the DG through a set of energy storage systems (ESSs) owned by the distribution network operators (DNOs) that will be in charge of the mismatches between generation and demand.

The main objective of this project is to develop the control of distribution networks with the integration of dispersed energy storage systems with Multi-Agent system approach. More precisely, a hierarchical approach will be used distinguishing different levels of importance within the ESSs where the flow of information will be done between the different levels.

Firstly, a brief introduction will be given on the background, the current situation of electric power systems and the general principle of the algorithm of control. Then, the first layer of control will be presented, where a preliminary distribution control will be run through Economic Load Dispatch concept, neglecting so far the losses in transmission lines adapting it to the case of ESSs. Subsequently, the following layer will be tackled by running the load flow on the different areas. For such task, special attention will be given to the issue of the influence of the external part of the system to the load flow of a certain area. Several proposals were studied although only the best solution, the decomposition method, will be presented. The other approach, Ward Equivalent, is briefly described in the annex of this report. Finally, some conclusions will be drawn based on the results obtained as well as the following steps to tackle.

# DECLARATION

This report summarizes the main areas of development of the Master Semester Project in Electrical Engineering at École Polytechnique Fédérale de Lausanne. It is worth mentioning that the tasks developed during this time take part of a larger project: the Thesis of PhD candidate Maryam Bahramipanah at EPFL. Consequently, the area of focus of the project will only be in certain parts of the vast problem at stake while taking for granted and making use of progresses done beforehand that will be considered as given inputs to this project. All other sources of information have been duly acknowledged in the References section.

# Contents

# TABLE OF FIGURES

# GLOSSARY

| | |
|---|---|
| *DG* | Distributed Generation |
| *DNO* | Distribution Network Operators |
| *ELD* | Economic Load Dispatch |
| *ESS* | Energy Storage System |
| *HV* | High Voltage |
| *LF* | Load Flow |
| *LV* | Low Voltage |
| *MAS* | Multi-Agent System |
| *MV* | Medium Voltage |
| *OPF* | Optimal Power Flow |
| *RES* | Renewable energy sources |
| *SoC* | State of Charge |
| *SSEG* | Small-Scale Embedded Generation |

# 1 INTRODUCTION

## 1.1 BACKGROUND

Historically, power systems were structured in such a way that generation and consumption were completely differentiated and far from each other. Generation used to be done in large power plants of various natures such as coal, nuclear power or water while the largest cores of distribution were concentrated in the cities where the largest part of the population made use of that energy. The link between them was done through High Voltage lines of hundreds of kilometers with the aim of minimizing the losses in the transmission associated to Joule effect. This lead to a unidirectional power flow as shown in Figure 1 with a clear hierarchical structure and whose control was mainly focused on reliability and quality of supply. To fulfill such requirements, Distribution Network Operators (DNOs) ensured the correct performance at High and Medium Voltage levels.

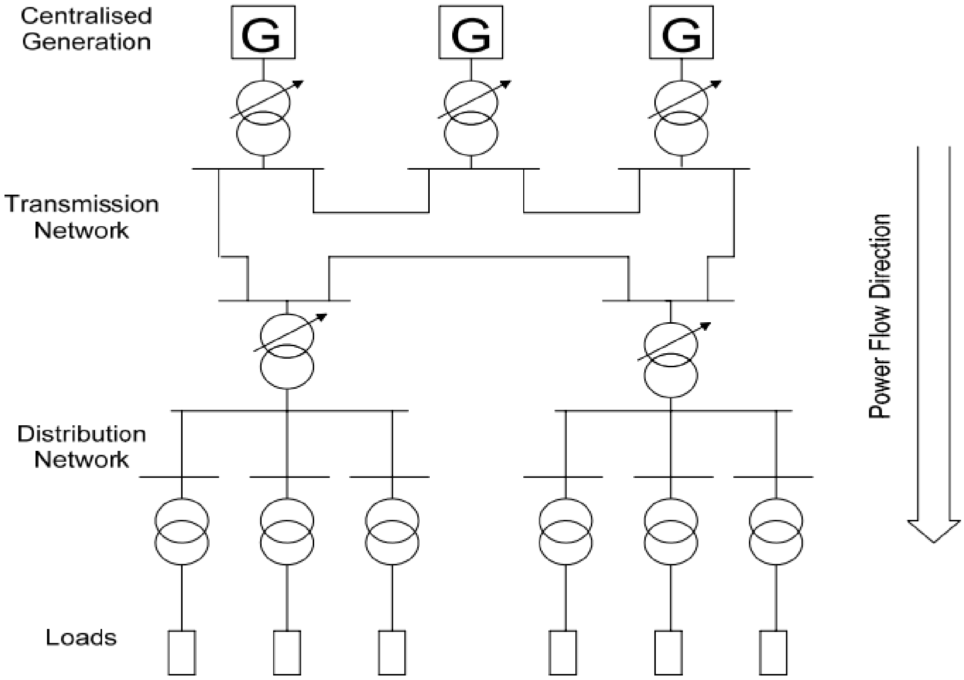

*Figure 1. Traditional structure of electrical power systems*

However, in recent years and due to the new environmental regulations there has been a significant increase in the penetration of Renewable Energy Sources, which are no longer concentrated in large and remote places but increasingly implemented in DG at the Medium Voltage level or in Small-Scale Embedded Generation (SSEG) at the Low Voltage level. This has several potential advantages since it would mean, among others, the reduction of the use of the HV lines since power consumption would be done nearer from its generation. Nevertheless, power systems as they are structured nowadays, do not collect direct data from LV level according to what is known as "fit-and-forget" control approach. Traditionally, this was not a problem because, as the power flow was unidirectional, controlling the flow at MV was enough to guarantee the correct performance of the system. But from the moment when generation is done at the LV level, the power flow may change to be bidirectional, as in Figure 2, and therefore, putting in danger the reliability of the system if no further action is taken.

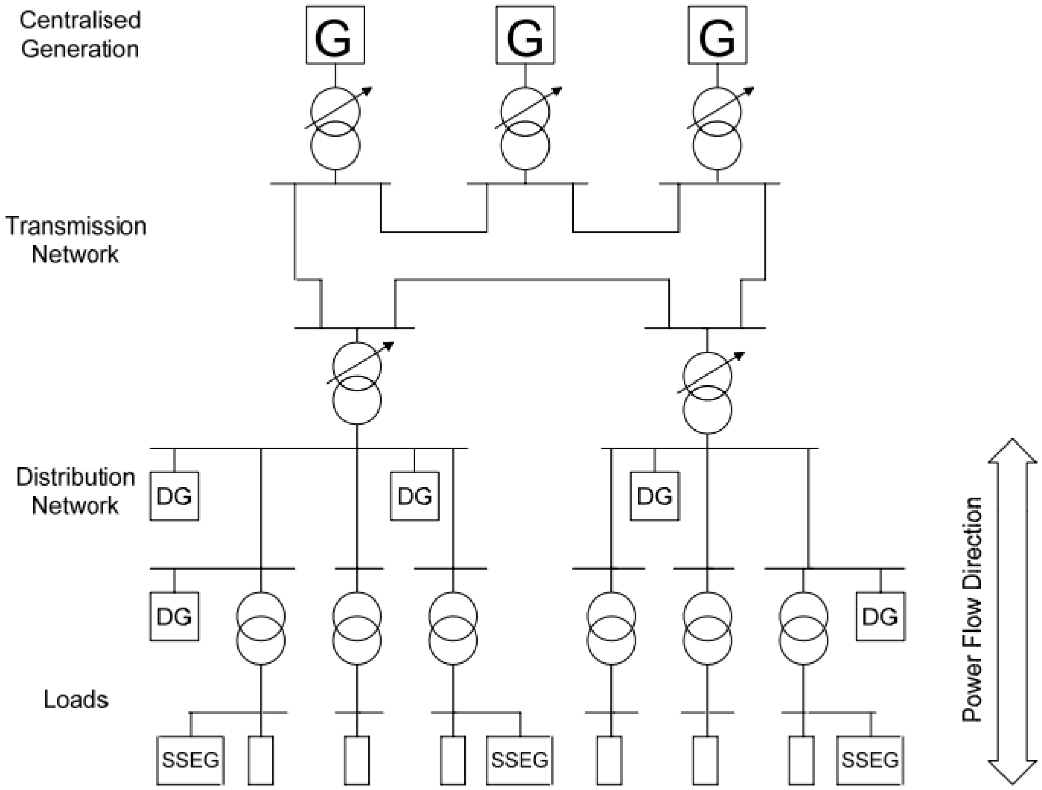

*Figure 2. Structure of electrical power systems with DG and SSEG*

Continuing with the passive approach at LV level, a solution to this issue could be to overrate the capacity of the system in order to avoid overcharging certain lines. But this seems more like a temporary solution, due to the ineludible increase in future power demand, as well as risky since DNOs would still not have any control over LV components of the system. A more suitable approach is to move towards an active philosophy of control at LV level, by actually regulating the generators at this stage. This, however, presents the disadvantage of the vast amount of data available at this level. For such reason, this paper proposes the introduction of Energy Storage Systems (ESSs) together with the implementation of Multi Agent Systems approach.

## 1.2 ENERGY STORAGE SYSTEMS (ESSS)

Given the complexity of controlling all the participants of the network at LV level due to the dimension of the problem, especially because of the stochasticity in the generation of Renewable Energy Sources, an alternative method is presented. The focus will be on introducing Energy Storage Systems (ESSs) that will help smooth the possible fluctuations in both generation and demand. By the effect of these ESSs, it is possible to control the Voltage levels of the network in order to keep them within a certain desirable value as well as controlling the power flow in the network.

An important aspect of ESSs is that they are not only able to provide energy, but of course to store it whenever it is required by the system. This provides a whole new operation mode compared to energy generators' control which can only vary the power supplied within a positive amount. Some examples of ESSs are hydraulic power plants or flywheels, as that of Figure 3, where energy can be stored in moments of low activity and supplied in peaks of demand.

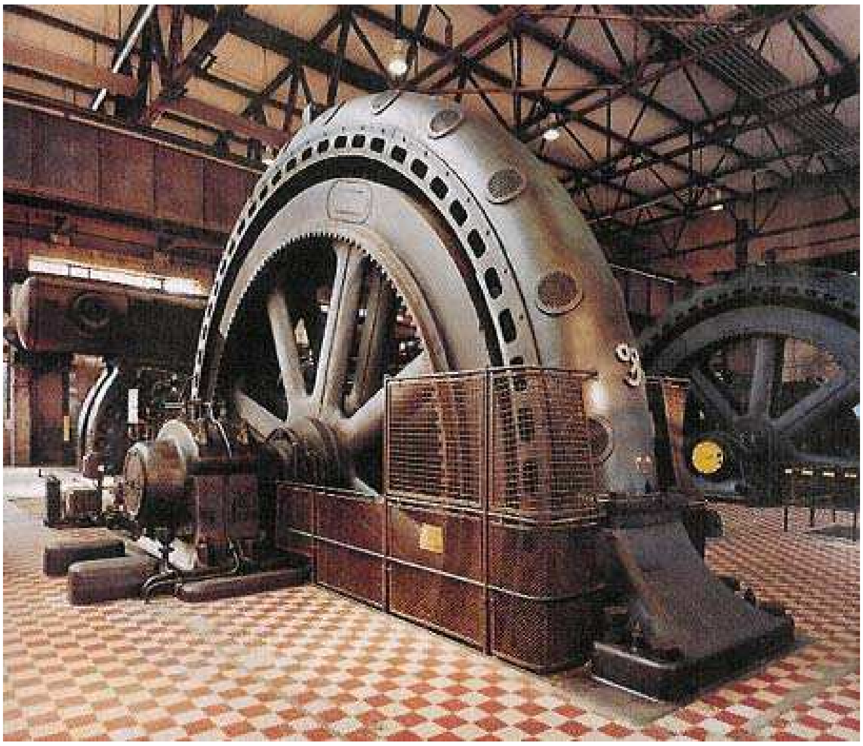

*Figure 3. Example of ESS: Flywheel*

Another key factor of the ESSs is that, as any other battery, it is subject to a certain capacity available (amount of energy it is able to provide) unlike traditional power plants which limitation is in the instantaneous power capable of providing although "theoretically" unlimited over time. This will be of capital importance through the development of this study.

It is worth mentioning that the location of the ESSs may also have a strong influence on the result of the project but at this stage was considered as predefined.

## 1.3 MULTI AGENT SYSTEMS (MAS) APPROACH

### 1.3.1 Concept

The principle behind this method is the integration of the ESSs in the MAS approach. MAS approach, as explained in [1], aims at breaking down a complex problem into smaller tasks which are delivered to the different "agents", in this case the ESSs, that will be in charge of solving the problem. Even though the agents are not aware of the whole problem, they are capable of solving their subtasks, obtaining as an overall result the correct performance of the whole system.

With this objective, the system is partitioned into several areas, each of which is assigned at least one agent. A wise selection of the areas is key to the correct functioning of this method. This issue was already tackled in previous studies using voltage sensitivity for the grouping of buses and was therefore given beforehand.

The objective is to achieve moderately independent areas in which there are generators, loads and ESSs (agents) so that they are as autonomous as possible, in order to reduce the interdependence of the system, dangerous in cases of contingency. That way, errors in one of the areas would affect in a small way to the rest of the system.

Generally, MAS models may be classified following their communication methodology as follows:

- Peer-to-peer: Communication is done between neighboring areas, all interconnected through a cyber-layer which is different to the actual physical layer which indicates the real power connections. There are no levels of relevance within the ESSs, which influence the rest of the system with the same proportion. Figure 4 shows the interconnection of all agents.

*Figure 4. Peer-to-peer structure for MAS approach*

- Hierarchical: In this case, several layers are available according to the relevance of the ESSs within the system which are coordinated by a central agent. Besides the central agents, within each area, “master” and “slave” agents are defined beforehand. The information flow is vertical, making “slave” agents rely on “master” agent’s decisions.

Both of them present advantages and constraints in different domains. However, throughout this project the hierarchical approach will be investigated since a parallel project focused on the peer-to-peer model. The general working methodology will be presented in Section 1.3.2.

### 1.3.2 Hierarchical MAS algorithm

As stated before, hierarchical MAS structures the information flow in a vertical way, having several levels with different tasks. The amount of levels in a system strongly depends on its size, although for a sufficiently large system three levels will be developed. A general view of the system is presented in Figure 5.

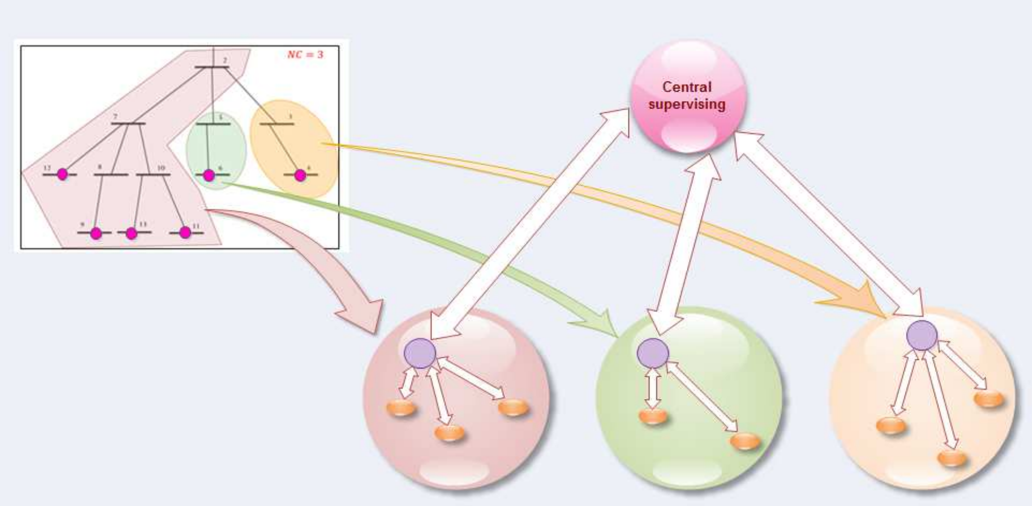

*Figure 5. Hierarchical structure for MAS approach*

The first level is based on a central agent, which is the link between the different areas. Therefore, its main task is to obtain the preferred power flow between each of them. An important concept is that for this central agent, the internal states of each area are unknown. However, based on the aggregation per area, for each time step the internal loads and generations are added so that the whole area is seen either as a load or a generator making it possible for the central agent to run the power flow.

For the following level, the power flow in the different areas will be undertaken with the main objectives of efficiency and safety within each area. For that purpose, the Optimal Power Flow (OPF) will be implemented as a combination of both economic and technical factors. The agents in charge of this task will be the "master" agents of each area. This level will take as a first solution the results obtained in the previous level. However, at this point losses will also be taken into account changing substantially the real solution from the theoretical one obtained before.

Furthermore, a third level of control will be necessary for sufficiently large systems which, in practice, almost all will be. For such cases, more than one agent will be necessary in order to correctly cope with the fluctuations of the voltage levels through the network. The third level will take care of ensuring that the "slave" agents within the different areas fulfill the conditions set by the previous level so that accordance between both is fulfilled.

## 1.4 OBJECTIVES

In the frame of a thesis to propose the control of distribution network with the integration of dispersed ESSs with MAS approach the main objective attained in this project is to develop and implement the hierarchical approach. The main tasks completed throughout the project can be summarized as follows:

- Develop the first level of control through ELD concept.
- Construct the second level of control with a special focus on taking into account the effect of the external areas on the LF of a certain area.

## 1.5 PLANNING

The planning followed during the project can be seen in Annex A, where the different parts developed during the project are defined specifying the length of each activity. It is worth mentioning that the planning was modified during the process due to issues that arose while completing it.

# 2 FIRST LEVEL OF CONTROL

Once the topic was understood through bibliography revision, the first level of control was tackled. This level must calculate the desired power flow between areas. For such task Economic Load Dispatch (ELD) will be employed. In this section, a brief description of ELD will be given, focusing on the advantages and objectives it presents. Then, the general formulation of an ELD problem will be described after which the adaptations done to the specific case of ESSs will be discussed, including the solution proposed to this issue. Finally, results from simulations will be shown to prove the correct functioning of the algorithm.

## 2.1 CONCEPT

ELD, as defined in [2], is used to distribute the power between several generating units in order to maintain the balance between generation and demand. The selection of the output of each generating unit is done in such a way that total costs derived from controlling the system are minimized. At this stage, power losses will be neglected since this layer will give a general overview of the system and, therefore, a high accuracy is not necessary while computational efficiency is indeed an important factor.

## 2.2 GENERAL PROBLEM FORMULATION

Cost functions of generators are usually modelled as second-order equations as that of (1) since there is a constant term, $C_i$, which models the fixed costs associated to opening a generator, independently of the amount of power $P_i$ produced, and also the variable costs, related to $\alpha_i$ and $\beta_i$, which increase quadratically with the amount of power delivered. Graphically, the cost functions of three generators are presented in Figure 6.

$$C_i = \alpha_i {P_i}^2 + \beta_i P_i + C_i \tag{1}$$

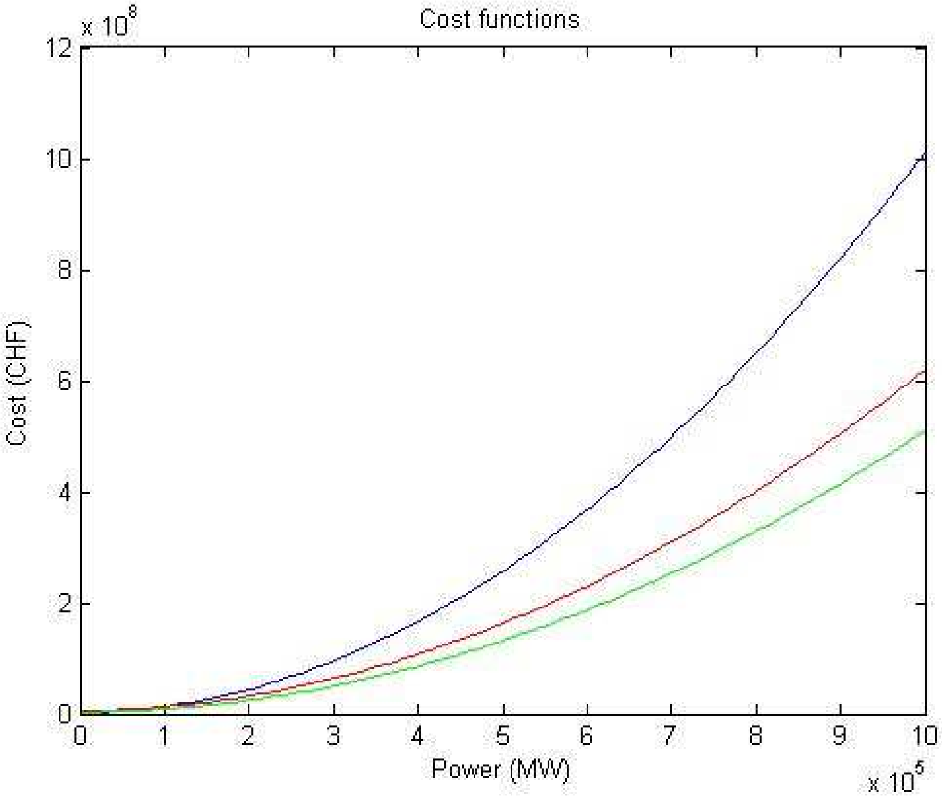

*Figure 6. Cost function of three generators*

ELD must look for the optimal point where the sum of the costs of the generation is minimized. This is done through the Lagrangian method. This method optimizes an objective function, in this case minimizing total costs, subject to an equality constraint, which is that the total increase in demand must be covered by generation. This function is shown in (2) where $\Delta P_D$ is the total variation in demand in the system, $\sum C_i$ is the sum of the costs of generation and $\lambda$ is the Lagrangian operator.

$$L = \sum C_i + \lambda(\sum P_i - \Delta P_D) \tag{2}$$

According to the Lagrangian method, the derivatives with respect to all of the variables, including the Lagrangian operator, must be equal to zero, what conveys as a solution equation (3).

$$\frac{dC_i}{dP_i} = \cdots = \frac{dC_n}{dP_n} = \lambda \tag{3}$$

Therefore, the derivatives of the cost functions must be equal in order to obtain the optimal solution. This result is quite intuitive and can be easily explained given an example. Should it be the case where the derivative of one of the cost functions was different from another, this would mean that producing an extra megawatt of power in the generator with smallest derivative would have been cheaper than doing so in the one with higher derivative, violating therefore the objective sought with this method.

An example of the method can be seen in Figure 7, where for a given power demand, the power output of the generators are such that their derivatives are equal.

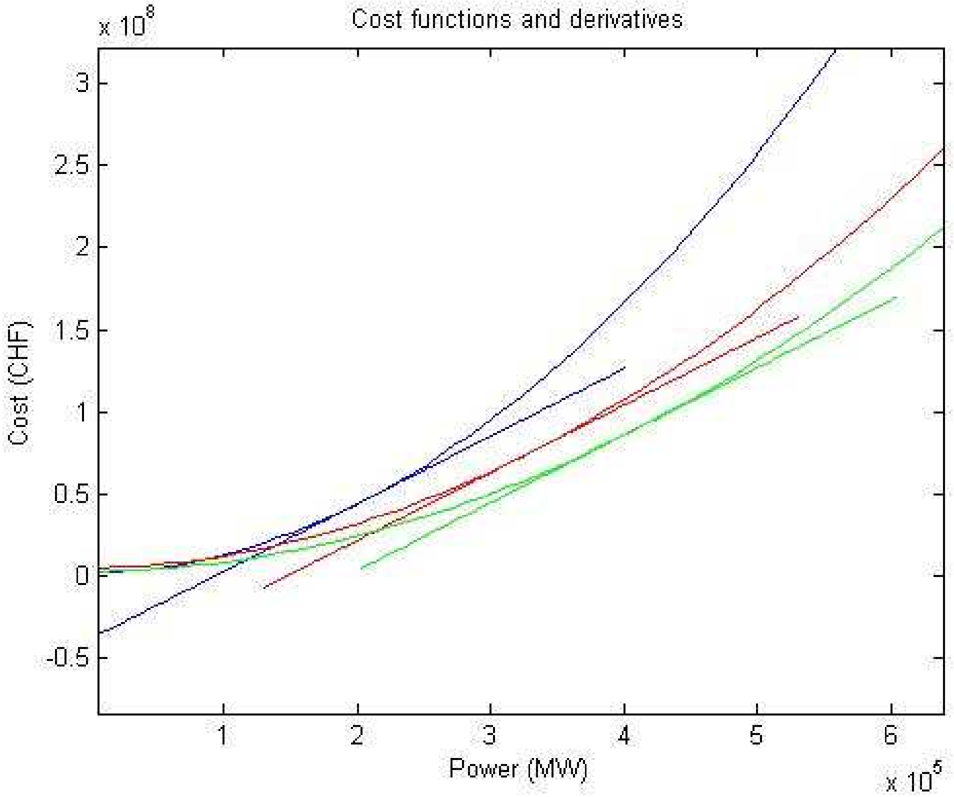

*Figure 7. Cost functions and derivatives at a certain point of operation*

## 2.3 ADAPTATION TO ESSS

So far, ELD has been presented in the conventional way applied in literature or, in other words, for generators. Also, constraints such as the maximum power of a generator or the losses in the transmission lines have been neglected. For our particular case, some important variations will be necessary with respect to the base example to more accurately describe the situation that will be proposed.

More precisely, the ELD model will have to be altered by transforming the cost function of the generators in order to be suitable for the ESSs. The new cost function (4), where $SoC_i$ is the state of charge of the ESS, will be explained in the following subsections. There are two main reasons for these changes: the storage mode and the limited capacity of ESSs.

$$C_i = \underbrace{\left(1 + sign\left(\sum P_i\right) \cdot 1.5 \cdot (0.5 - SoC_i)\right)}_{\text{Limited capacity}} \cdot \underbrace{(\alpha_i |P_i|^2 + \beta_i |P_i| + C_i)}_{\text{Storage mode}} \quad (4)$$

### 2.3.1 Storage mode

The first large modification will be regarding the fact that the control agents in this network are ESSs in opposition to regular generators traditionally employed in ELD. As explained in Section 1.2, ESSs, as their name implicitly define, have a storage mode as well as the generator mode. In those cases in which the system has a greater amount of energy than what is needed to be consumed, ESSs will be able to absorb the energy to relieve the system. This implies that a definition of the problem for negative amounts of power (storage mode) will be necessary.

Several approaches were debated regarding the storage mode. The discussion mainly focused on whether this mode should incur in positive or "negative" costs (revenues) for the system. Storing energy could be seen as a sale (revenue) from the system to the ESSs which should pay for that energy although they were not going to consume it. On the other hand, this action could also be seen as a "favor" that the ESSs do to the system since they take charge of the exceeding generation and, in consequence, is something they should be paid for.

A key factor that was taken into account in the decision-making process was related to the ELD nature of the problem. Following the example presented in Section 2.2, the Lagrangian solution converges to a point where the derivatives of the cost functions are equal because, otherwise, having a smaller derivative would imply that it would have been cheaper to produce the last MW of power on that generator than in the one with highest derivative. However, if negative costs are introduced in the system, the minimizing solution is no longer achieved when the derivatives are equal, therefore being unable to use the ELD and being obliged to use more complex methods. Again, this may be better understood with the example presented in Section 2.2. In storage mode, where negative costs would mean revenues for the system, in case that the derivatives of the cost functions were different, an extra MW would be preferably stock in the one with the largest derivative in absolute value as it would imply larger revenues. This would lead to an ordered filling of the ESSs, starting from the one with highest derivative and going on with the next one only when the previous one is full.

For that reason, positive costs were chosen both for generation and storage. Up to a certain extent, it may also be understood as taking into account a cost for transmitting the power from generators to storage systems, and finally to consumers. All this incurs into higher costs that with the other approach would not be accounted for. In practice, this was implemented in (4) by computing the absolute value of the power supplied or stored. Summarizing, the power will be now free from the constraint of positive power but will continue to be constrained to positive costs as shown in Figure 8.

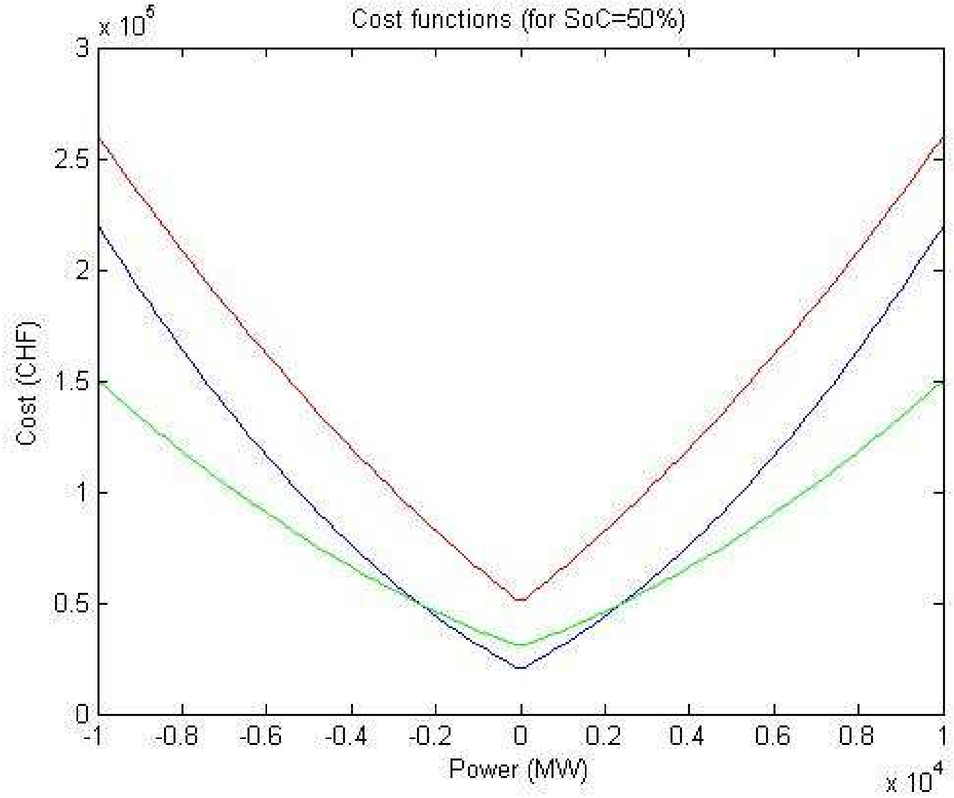

*Figure 8. Cost function of three ESSs for a SoC of 50%*

### 2.3.2 Limited capacity

As explained in Section 1.2, ESSs have a limited capacity, reason why saturation of the agents will be necessary when capacity is either empty or full. For such purpose, a new variable will be computed to know at each moment the amount of energy available in a certain ESSs. It is worth pointing out that no limitation will be considered regarding the power delivered at each time step, but only with respect to the energy available in the ESS. Of course, whenever an ESS reaches its full (or empty) capacity, it must saturate so that no further power is stored (or delivered) in this ESS.

However, this situation is not desirable since reliability could be dangerously harmed. Whenever an agent saturates, it will no longer be useful for the system which will go on to rely on less agents. In the event of failure of one of the non-saturated agents, the system will be more exposed to difficulties, or even a blackout in the worst possible scenario. To avoid this from happening very frequently, the ESSs' cost functions were modified in order to depend on the state of charge (SoC), as can be seen in (4).

| | **∆ Ptot>0 (supply needed)** | **∆ Ptot<0 (storage needed)** |
|---|---|---|
| $SoC = 0.5$ | $(\alpha_i\|P_i\|^2 + \beta_i\|P_i\| + C_i)$ | $(\alpha_i\|P_i\|^2 + \beta_i\|P_i\| + C_i)$ |
| $SoC = 0.9$ | $0.4 \cdot (\|P_i\|^2 + \beta_i\|P_i\| + C_i)$ | $1.6 \cdot (\alpha_i\|P_i\|^2 + \beta_i\|P_i\| + C_i$ |
| $SoC = 0.1$ | $1.6 \cdot (\alpha_i\|P_i\|^2 + \beta_i\|P_i\| + C_i$ | $0.4 \cdot (\|P_i\|^2 + \beta_i\|P_i\| + C_i)$ |

*Table 1. Effect of state of charge on ESS cost functions*

Table 1 shows some examples of how the SoC affects the cost functions. The principle behind this modification is that an ESS will be willing to supply energy, and therefore offer a cheaper price for its energy, when it is charged over 50% of its capacity and the opposite way round. The equilibrium point is at 50% where neither additional charge nor discount are done to the cost function. Taking the example where there is an increase in demand, ∆ Ptot>0, and therefore supply is requested to the energy storage system, the costs associated are increased (or decreased) in 60% in the case where the ESS is full up to 10% (or 90%). Graphically, the cost functions for both supply and storage depending on the state of charge were plotted in Figure 9.

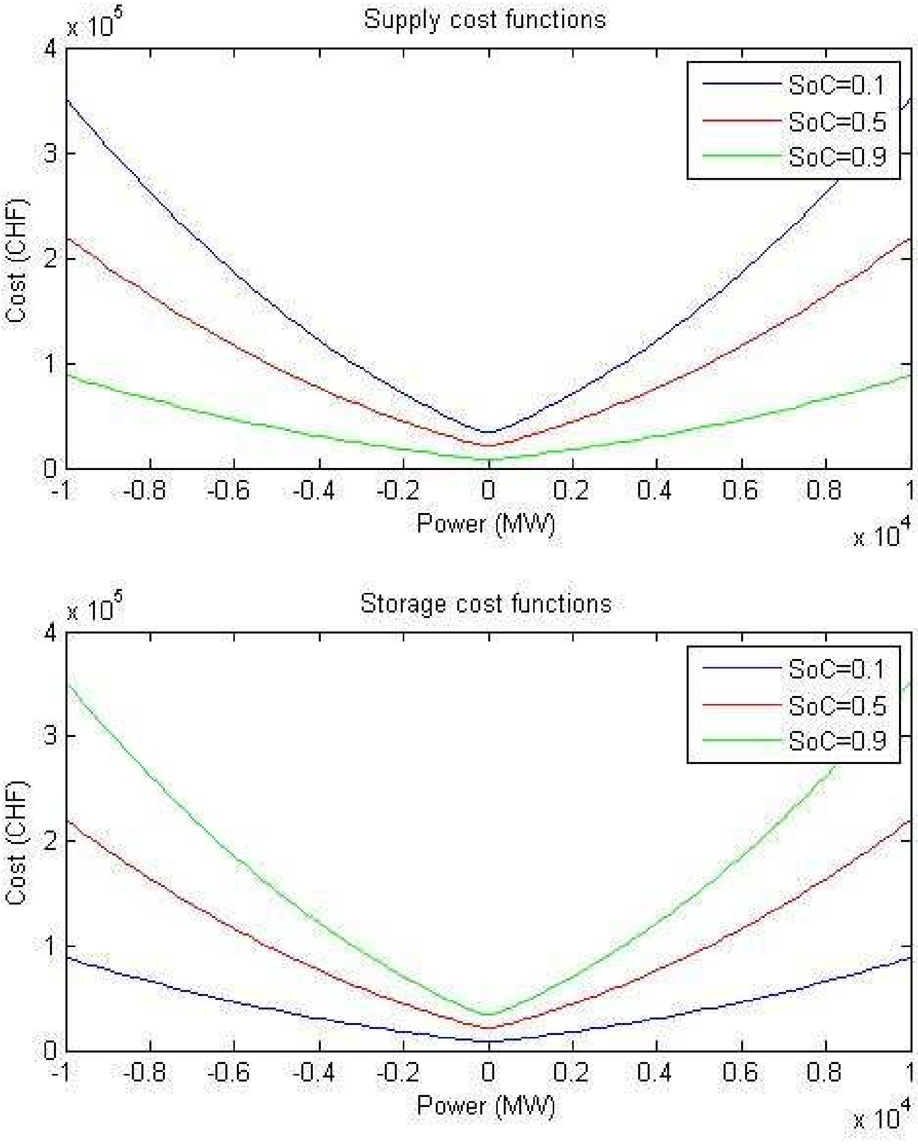

*Figure 9. Supply and storage cost functions of a single ESS depending on the state of charge*

## 2.4 SIMULATION

With the problem already defined and adapted to the requirements, the method was implemented for a 13-bus system divided in three areas as the one in Figure 10, where ESSs' locations are also defined. At this stage, the mean load will be assumed to be covered by the generators of the system while the ESSs will be accounted for the fluctuations over that point. The MATLAB Code is enclosed and can be revised in Annex B.

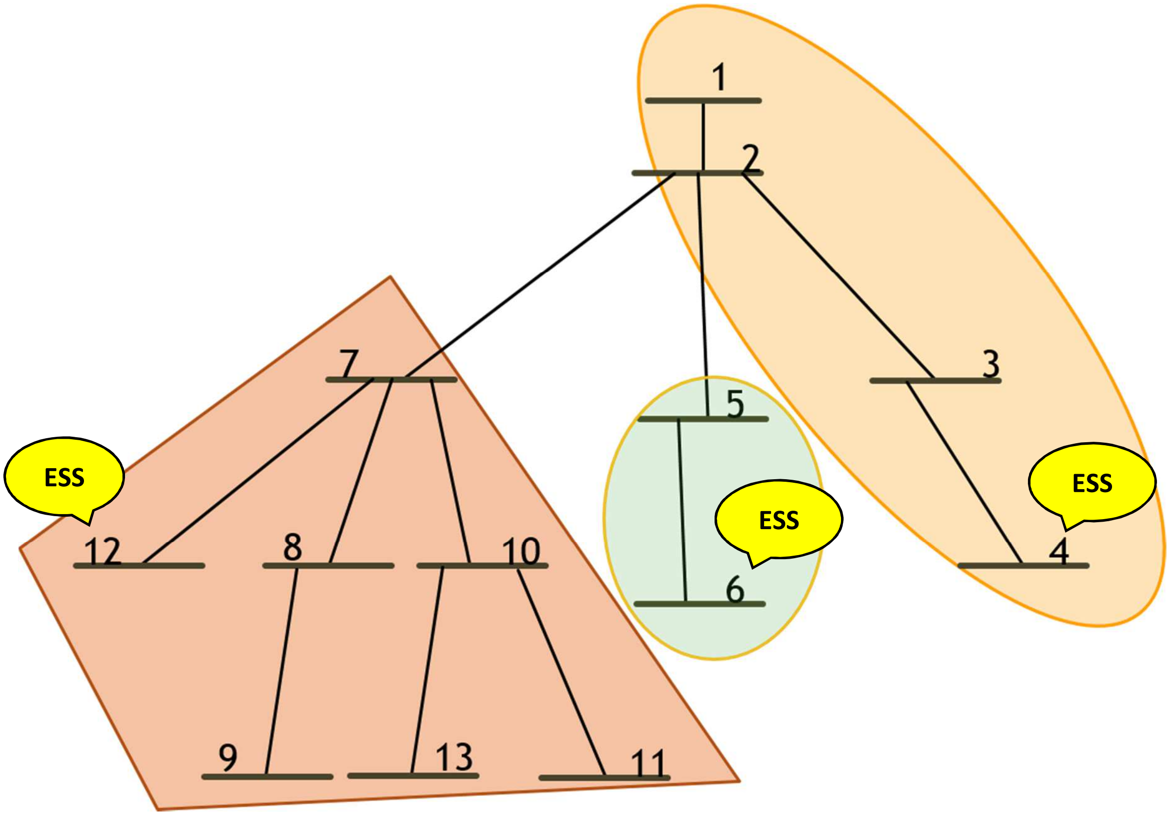

*Figure 10. 13-bus model aggregated in three areas*

## 2.5 RESULTS

From the simulation, some graphs were obtained which support the correct performance of the ELD model. From Figure 11, the most relevant conclusions are:

- As expected, when the ESSs are not saturated (SoC different from 0 or 1), the derivatives of the cost functions are equal within a certain tolerance.
- Complementary to the previous point, when an ESS saturates, its power supply drops to zero as it is no longer able to participate in the system's tasks until there is a change from demand to storage, or vice versa.
- The one with smallest costs (green), known from Figure 8, almost always is selected to supply and store the largest quantity of power. This concept might seem incompatible with

the second chart as the ESSs that saturate are the other two. However, this happens because the ESS sizes of the other two are smaller than the green one.

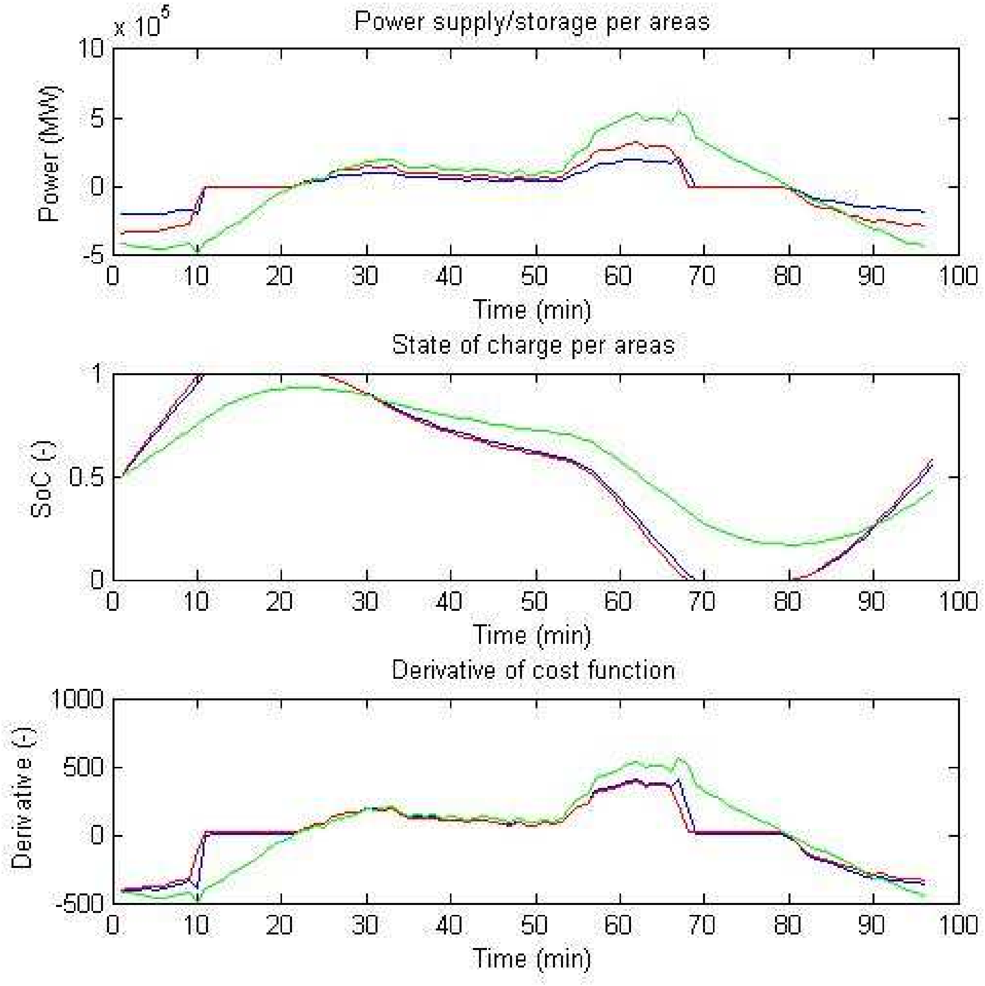

*Figure 11. Power supply/storage, SoC and derivative of the cost function per area*

Figure 12 presents the generating cost, as well as the power generation and SoC, which were already presented. The reason is that it is interesting to see the effects between them to be able to more wisely notice the correct performance of the system. From this figure, it is worth mentioning the following:

- For a reasonably flat storage of power as the one obtained in the first ten time steps, with the conventional method, costs would remain constant. However, due to the influence of the SoC in the cost functions, since the last one increases, so does the generating cost as it is shown in the third chart. This is also noticeable at time steps around 60 with a flat injection of power.
- At the moment where saturation is reached by the ESSs, the one that is still active suffers a peak due to the overload from taking over the contribution that was being provided by the other ESSs. This peak is more noticeable in the costs for the reason explained in the previous point.

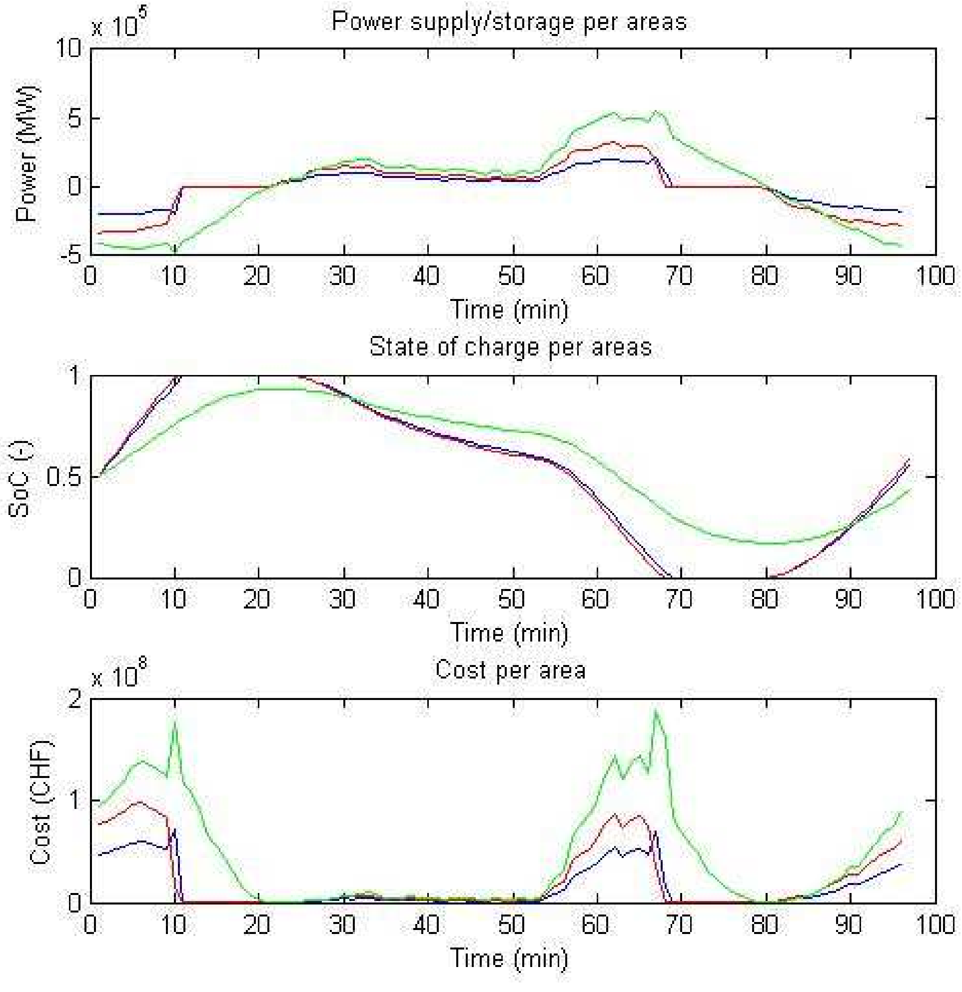

*Figure 12. Power supply/storage, SoC and cost per area*

## 2.6 CONCLUSIONS

From the results presented in Section 2.5, the adaptation of the ELD model for ESSs is satisfactory and can be used with the objective set beforehand of giving an overview of the general power flow that should be sent between areas. These results will serve as a broad idea for the following layers to implement the load flows in the different areas. However, variations from this basic information will show up given that energy losses were neglected so far.

Annex B presents the MATLAB Code developed through the project which can be employed to any system defined by the basic information (number of buses, ESSs' information, etc.). This code can be adapted and employed for future studies in other systems.

The most significant breakthrough of this part of the project is the adaptation of the ELD concept to energy storage with its consequent dependence on its capacity and the incorporation of a storage mode which is of capital importance to the correct performance of the system. Also, the influence of the state of charge of the ESSs in the cost functions increases the reliability of the system with respect to possible contingencies, improving the overall rating of the system.

# 3 SECOND LEVEL OF CONTROL

In the second part of this project, the following level was approached. As stated in Subsection 1.3.2, the principle behind this level will be to run the Optimal Power Flow (OPF) in the different areas of the system starting from the solution obtained in the First Level. OPF can be understood as an enhanced Load Flow where economic factors are taken into account. This, of course, adds another degree of detail to the previous ELD due to the incorporation of losses as part of the problematic.

However, before the implementation of the OPF in the different areas can be done, there is a key point that must be tackled. Due to the partition of the system in distinct areas, it is compulsory to take into account the influence of "the rest of the world" in the LF of a certain area. In this section, this issue will be presented. Secondly, a decomposition method proposed to solve such task will be explained. Then, the method was tested both on a 13-bus and a 123-bus systems from which promising results were obtained. Finally, some conclusions will be presented on this subject. It is worth mentioning that other methods were undertaken prior to the solution presented in this report. To avoid further studies on topics already discarded, the non-adequate approaches can be found in Annex A.

## 3.1 ISSUE AND POSSIBLE SOLUTIONS

At this level, the "master" agents of each area will be in charge of running the LF. These agents will take care of the calculation of their own area while having the minimum knowledge about the other areas, as this is the definition of MAS approach. Nevertheless, running the LF in an area ignoring the other ones would be equivalent to completely isolated systems where the power flow between areas is inexistent which is another field of study, more similar to the MicroGrid concept as in [3] where autonomy between areas is pursued. Since in this case, the power flow between areas can and in fact does exist, a good approach on this topic becomes of capital relevance for the correct functioning of the approach.

The possible solutions studied during this project range from equivalencing the rest of the system by the Ward Equivalent method [4] to linking the boundary buses of the different areas according to the power flow in the tie-lines or the decomposition method. For the sake of simplicity, the last method will be the only one to be explained as it proved to be the most effective.

## 3.2 DECOMPOSITION METHOD

### 3.2.1 Concept

This approach, similar to that of [5], allows obtaining the operating point of a system without explicitly knowing data from the other areas. The only information transfer requested is the voltage at the boundary buses. By knowing these magnitudes, the power flow between areas will become known. In this method, the amount of power entering or exiting the area will be assigned to a fictive generator or load at the boundary bus, so that if there is a power flow going from Area 1 to Area 2, the boundary bus m of Area 1 will be assigned a load equal to the flow in the tie-line and the boundary bus k of Area 2 a generator of the same value, as shown in Figure 13. This will be done iteratively until convergence is reached.

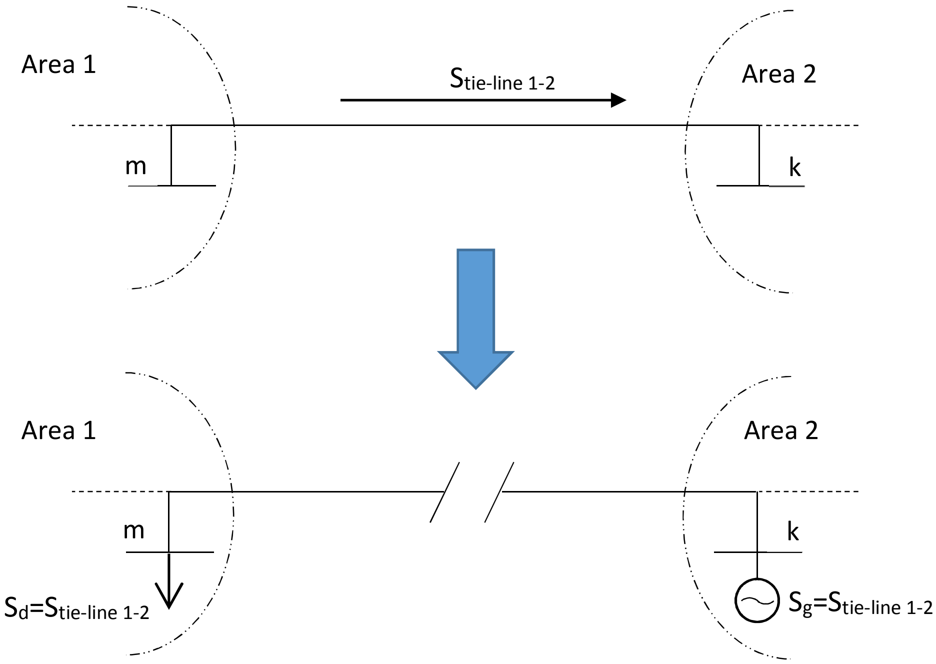

*Figure 13. Decomposition method principle*

The coordination process to follow can be resumed in the following steps:

i. The first step is to run the LF in the different areas. At the beginning of the process, this can be done as if they were independent (fictive generation and demand equal to zero).

ii. Share the voltage of the boundary buses to adjacent areas. With such magnitudes, and using equations (5) and (6), the power flow between buses k and m is obtained, where $G_{km} - jB_{km}$ is the admittance of the tie-line between both areas.

$$P_{tie-line} = \left(V_k^A\right)^2 G_{km} - V_k^A V_m^{AA} G_{km} cos\left(\theta_k^A - \theta_m^{AA}\right) - V_k^A V_m^{AA} B_{km} sin\left(\theta_k^A - \theta_m^{AA}\right) \tag{5}$$

$$Q_{tie-line} = -\left(V_k^A\right)^2 B_{km} + V_k^A V_m^{AA} B_{km} cos\left(\theta_k^A - \theta_m^{AA}\right) - V_k^A V_m^{AA} G_{km} sin\left(\theta_k^A - \theta_m^{AA}\right) \tag{6}$$

iii. Compare the power flow in the tie-lines with those obtained in the previous iteration. Should the difference be smaller than a certain tolerance, the process is finished. Otherwise, add the difference of power to the boundary buses (generation or load) and go back to step i.

### 3.2.2 Simulation and results on 13-bus system

This method was tested on the 13-bus system from Figure 10 where there are only two tie-lines and the slack buses of each area will be the ESSs. So far, it will be assumed that those ESSs have capacity enough to provide the energy necessary to satisfy the mismatches between demand and generation.

Results were very interesting for two of the three areas, as seen in Figure 14, where the voltage profiles of buses from Area 1 are shown in comparison with the conventional LF run for the whole system. Actually, the results obtained are almost equal to the conventional method, what clearly shows that the decomposition method correctly simulates the influence of the rest of the areas in the LF of a certain one.

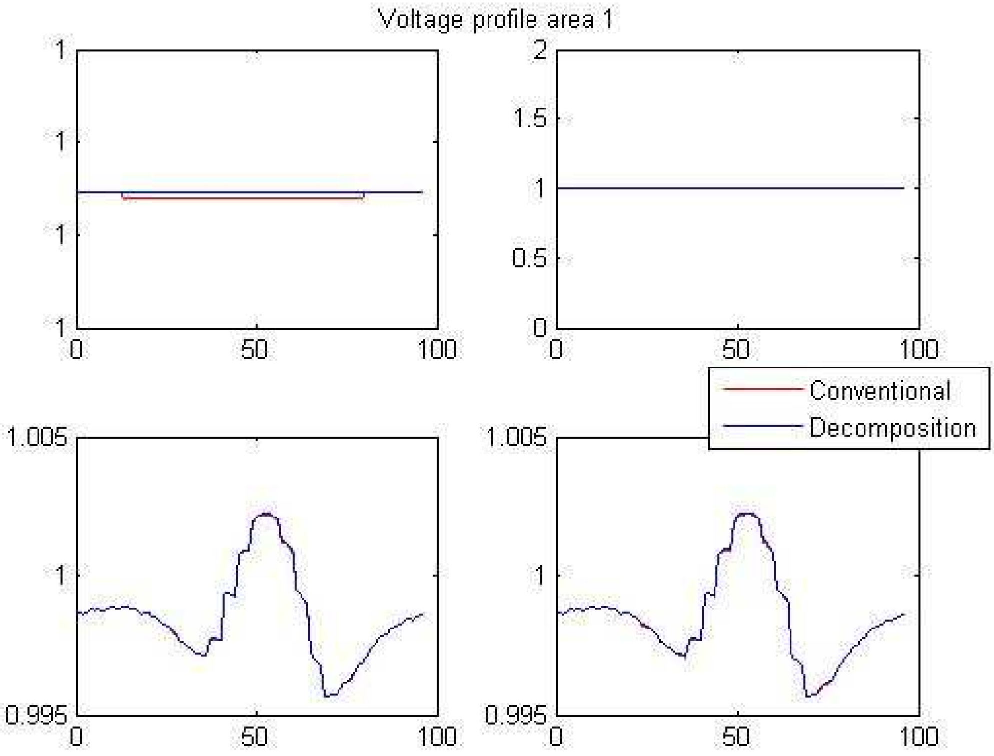

*Figure 14. Comparison of the voltage profiles of buses from Area 1 with the conventional and decomposition methods*

Nevertheless, for Area 2, the results obtained are unfortunately very unstable for one of the buses, as it is shown in Figure 15. A first conclusion could be the malfunctioning of the method. A second hypothesis was related to the fact that this area only has two buses, and one of them is of course slack bus for the decomposition method. Since the slack bus has its voltage equal to one, the other bus fluctuates in a large amount to compensate the hieratic performance of the other one. In order to test this hypothesis, a new test was done on a larger system.

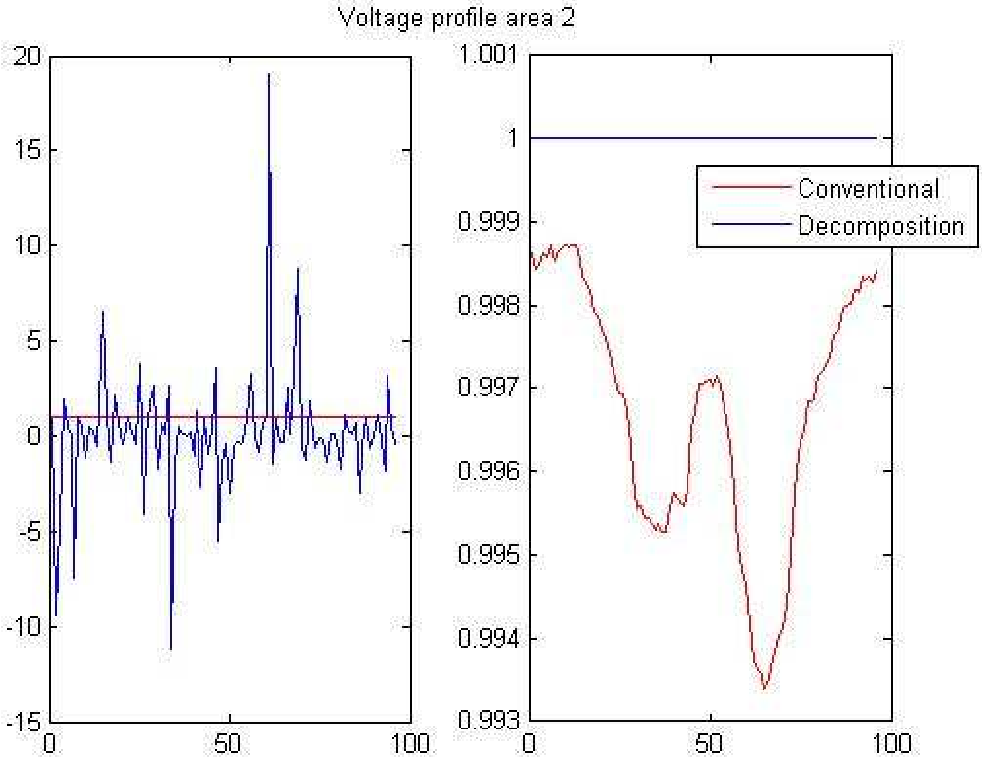

*Figure 15. Comparison of the voltage profiles of buses from Area 2 with the conventional and decomposition methods*

### 3.2.3 Simulation and results on 123-bus system

The method was then tested on a 123-bus system as that of Figure 16, divided in five areas, each of which with a single ESS. The same process was followed as in the previous test including the comparison with the central LF.

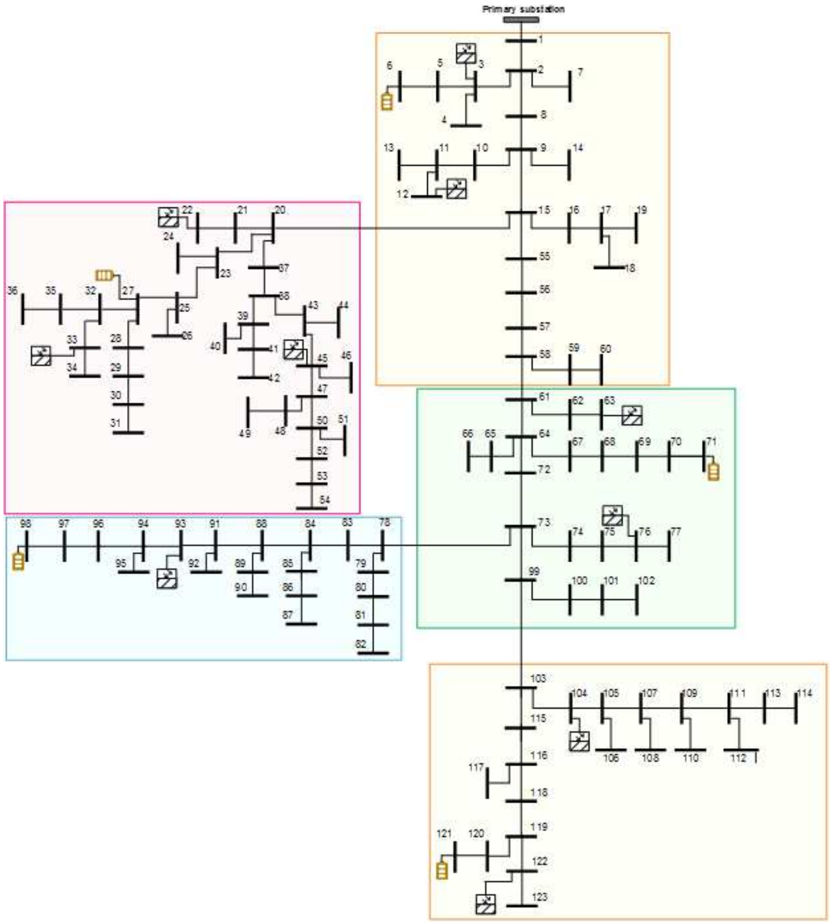

*Figure 16. 123-bus model aggregated in five areas*

From the implementation on this system, the results showed a larger variation between the decomposition method and the conventional one. This may imply that there is a dependence between the number of buses and the correct performance of the system what could reach up to a point where it is no longer acceptable. As it can be seen in Figure 17, the mean voltage drop in a random bus of the system is under 5% which is within the general acceptable threshold in distribution networks. It is worth mentioning that the results were independent to the selected slack bus, unlike the Ward Equivalent method implemented before with unsatisfying results as explained in Annex A.

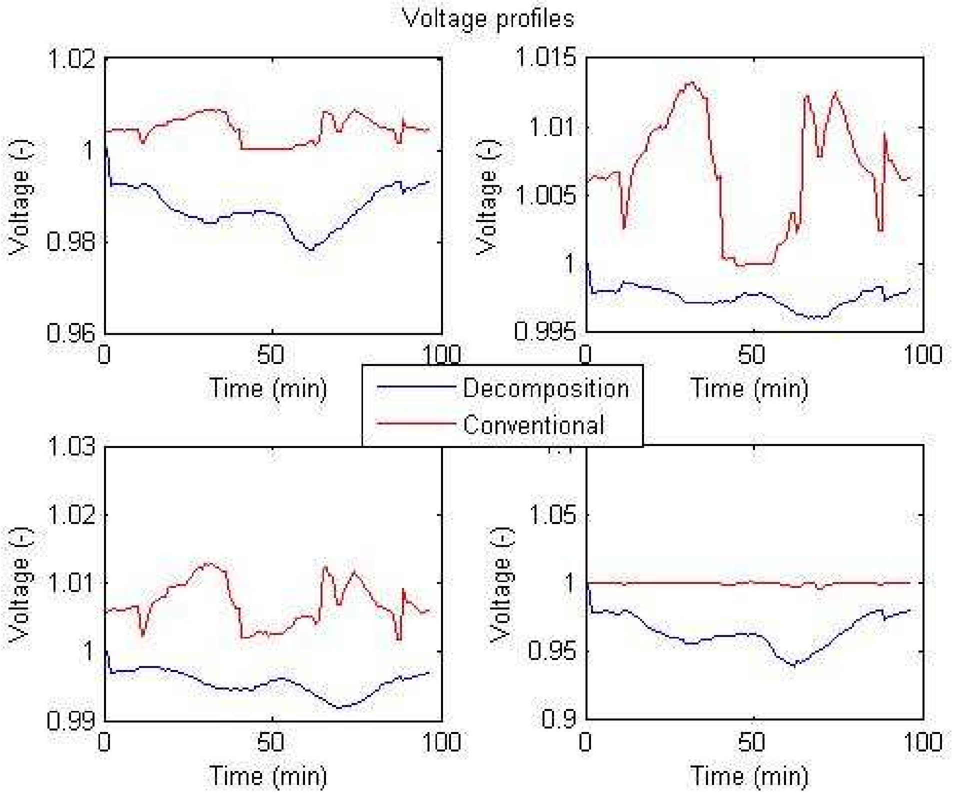

*Figure 17. Comparison of the voltage profiles of random buses with the conventional and decomposition methods*

## 3.3 CONCLUSIONS

The decomposition method explained previously seems the most advantageous solution for the task of determining the influence of "the rest of the world" to the LF run in a certain area. This is a key component to take into account before moving on to determining the strategy (either OPF or LF) within the different areas. The MATLAB Code developed through the project, which was done in a generic syntax is enclosed in Annex A and can be used for any system with the pertinent information.

The method presents especially good results for a medium-size system (123-bus system) while presenting some difficulties for really small systems. The reason is that for small size systems, the fixing of the voltage of the slack bus to a fixed value makes the rest of the voltages fluctuate in a great amount in order to converge to a reasonable result. It is still pending a test on a larger system to validate its accuracy due to the strong relationship between the size of the system and the difference between the conventional and decomposition methods overseen in the medium system.

In terms of time efficiency, the method proposed lags behind with respect to the conventional method due to the iterations that must be done to reach the solution. However, this was not one of the key drivers of this study. Instead, the objective of a coordination between the different systems so that the LF in each of the areas match between them including the effect applied by one to the other is accomplished. Moreover, in case that time efficiency becomes an important factor in future developments, the use of a more powerful software can always increase the computational efficiency of the algorithm.

It is worth mentioning that in all these experiments so far the conventional LF was implemented instead of the OPF proposed beforehand. The reason is that for all the systems treated in this report (13-bus and 123-bus) only one ESS was available in each area. Since the OPF defines the optimal economical way to distribute the energy supply between several generators (or ESSs in this case) but there was only one ESS per area, it will not be wise to use the OPF strategy until several ESSs are assigned to each area, or in other words, when also “slave” ESSs are available at the different areas.

# 4 CONCLUSIONS AND NEXT STEPS

The main conclusions of the improvements achieved during this project are summarized at the end of each chapter and can be revised in subsections 2.6 and 3.3.

As part of the project development, several steps must be taken to go on with the objectives searched for the Master Thesis. The most relevant steps that need to be taken in the near future are:

- Develop OPF strategy for the second level of control with the use of the decomposition method.
- Define the third level of control, between “slave” agents within each of the areas.
- Merge and coordinate all three levels of control.

# REFERENCES

[1] TRICHAKIS, PAVLOS (2009) *Multi Agent Systems for the Active Management of Electrical Distribution Networks*, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/57/

[2] DUNCAN GLOVER, J. (2008) *Power System Analysis and design*, Global Engineering, Cengage Learning.

[3] LASSETER, ROBERT; AKHIL, ABBAS; MARNAY, CHRIS; STEPHENS, JOHN; DAGLE, JEFF; GUTTROMSON, ROSS; MELIOPOULOUS, A. SAKIS; YINGER, ROBERT AND ETO, JOE (2002) *Consortium for Electric Reliability Technology Solutions White Paper on Integration of Distributed Energy Resources The CERTS MicroGrid Concept*, US Department of Energy

[4] SHI, DI (2012) *Power System Network Reduction for Engineering and Economic Analysis*, Arizona State University

[5] GRANADA ECHÉVERRI, MAURICIO; LÓPEZ LEZAMA, JESÚS MARÍA; SÁNCHEZ MANTOVANI, JOSÉ ROBERTO (2010) *Decentralized AC power flow for multi-area power systems using a decomposition approach based on Lagrangian relaxation*, Universidad Antioquía

[6] CHAYAKULKHEEREE, KEERATI - *Application of Distributed Slack Bus Power Flow to Competitive Environments*, IEEE, Sripatum University

[7] GÓMEZ EXPÓSITO, ANTONIO; MARTÍNEZ RAMOS, JOSÉ LUIS; RIQUELME SANTOS, JESÚS (2004) *Slack Bus Selection to Minimize the System Power Imbalance in Load-Flow Studies*, IEEE Transactions on Power Systems

# Annex A PLANNING

| PLANNING MASTER SEMESTER PROJECT | | | |
|---|---|---|---|
| Week 1 | 24-Feb | 02-Mar | Literature review on topic |
| Week 2 | 03-Mar | 09-Mar | |
| Week 3 | 10-Mar | 16-Mar | First layer strategy |
| Week 4 | 17-Mar | 23-Mar | |
| Week 5 | 24-Mar | 30-Mar | |
| Week 6 | 31-Mar | 06-Apr | Development of OPF for our strategy (Voltage control) |
| Week 7 | 07-Apr | 13-Apr | |
| Week 8 | 14-Apr | 20-Apr | |
| Week 9 | 28-Apr | 04-May | Second Layer strategy |
| Week 10 | 05-May | 11-May | |
| Week 11 | 12-May | 18-May | Third layer strategy |
| Week 12 | 19-May | 25-May | |
| Week 13 | 26-May | 01-Jun | Wrap-up and additional tasks |
| Week 14 | 02-Jun | 08-Jun | Wrap-up and additional tasks (if needed) |

# Annex B ELD – MATLAB CODE

## MAIN FILE

```
clear all
clc
close all
clear all

%Assuming that there are 3 areas already defined with following buses
%At first I will neglect the losses in the lines

n_areas=3;
end_time=96;
delta_t=24/end_time;%Time between periods expressed in hours

area1=[7 8 9 10 11 12 13];
area2=[1 2 3 4];
area3=[5 6];

%ESSs: Area, Bus location, generating cost(alpha, betha and Ci),
%Energy rated value, current energy value and current power value
ESS=[1   12   10e-4   10   2e4   1e6   .5e6   0
     2   4    6e-4   15   5e4   1.5e6   0.75e6   0
     3   6    5e-4   7   3e4   4e6   2e6   0];

ESS_P=zeros(n_areas,end_time);
ESS_soc=zeros(n_areas,end_time);%State of charge

ESS_soc(:,1)=ESS(:,7)./ESS(:,6);

Alpha=diag(2*ESS(:,3));%Define matrices for computation of Economic Load Dispatch (All eqs)

Const=ESS(:,4);

area_order=ESS(:,1);

n_bus1=length(area1);
n_bus2=length(area2);
n_bus3=length(area3);

n_buses=n_bus1+n_bus2+n_bus3;

deltaP_tot=0;
```

```
for k=1:end_time%Start in step 2, assuming that for step 1 the demand was
already compensated

    for bus=2:n_buses%Starts in 2 to skip slack bus. Calculates
increments of load with respect to previous period

        nameP=strcat('P',int2str(bus),'.mat');
        matP=load(nameP);
        Pi=matP.(strcat('P',int2str(bus)));
        deltaP_tot=deltaP_tot+Pi(k)-mean(Pi(:));%Variation around
operating point (mean value)

    end

    Alpha_r=Alpha;
    Const_r=Const;
    unlim_areas=n_areas;
    area_order_r=area_order;

    Gamma=diag(1+sign(deltaP_tot)*1.5*(0.5-ESS_soc(:,k)));
    Alpha_r=Gamma*Alpha_r;
    Const_r=Gamma*Const_r;

    z=0;%OK. With a 1 end while loop. With a 0, repeat it.
    m=0;%If a number is changed at its maximum, do not check the minimum
in the same iteration

    if deltaP_tot<0 %To do the absolute value

        Alpha_r=-Alpha_r;

    end

    while z==0&&m==0

        z=1;%By defect, finish the loop unless limits are reached
        m=1;

        if unlim_areas>1

            deltaPg=Lagrangian(Alpha_r,Const_r,deltaP_tot,unlim_areas);

            for i=unlim_areas:-1:1%Check if upper limit is reached

                area_ord=area_order_r(i);
                Emin=0;
                Ecurr=ESS(area_ord,7);
                deltaPgi=deltaPg(i);

                if (Ecurr-deltaPgi*delta_t)<Emin
```

```
                ESS(area_ord,7)=0;
                Pgnew=(Ecurr-Emin)/delta_t;
                ESS(area_ord,8)=Pgnew;
                deltaP_tot=deltaP_tot-(deltaPgi-Pgnew);

                Alpha_r(i,:)=[];
                Alpha_r(:,i)=[];
                Const_r(i)=[];
                %P_prev(i)=[];
                unlim_areas=unlim_areas-1;
                area_order_r(i)=[];
                z=0;
                m=0;

            end

        end

        if m==1%No maximum reached. Check minimum then

            for i=unlim_areas:-1:1%Check if upper limit is reached

                area_ord=area_order_r(i);
                Emax=ESS(area_ord,6);
                Ecurr=ESS(area_ord,7);
                deltaPgi=deltaPg(i);

                if (Ecurr-deltaPgi*delta_t)>Emax

                    ESS(area_ord,7)=Emax;
                    Pgnew=(Ecurr-Emax)/delta_t;
                    ESS(area_ord,8)=Pgnew;
                    deltaP_tot=deltaP_tot-(deltaPgi-Pgnew);

                    Alpha_r(i,:)=[];
                    Alpha_r(:,i)=[];
                    Const_r(i)=[];
                    %P_prev(i)=[];
                    unlim_areas=unlim_areas-1;
                    area_order_r(i)=[];
                    z=0;
                    m=0;

                end

            end

        end

    else
```

```
            if unlim_areas==1

                area_ord=area_order_r(1);
                Ecurr=ESS(area_ord,7);
                ESS(area_ord,8)=deltaP_tot;
                ESS(area_ord,7)=Ecurr-deltaP_tot*delta_t;
                deltaP_tot=0;

            else

                Error=k

            end

        end

    end

    if unlim_areas>1

        for i=1:unlim_areas

            area_ord=area_order_r(i);
            Ecurr=ESS(area_ord,7);
            ESS(area_ord,8)=deltaPg(i);
            ESS(area_ord,7)=Ecurr-deltaPg(i)*delta_t;

        end

        deltaP_tot=0;

    end

    ESS_P(:,k)=ESS(:,8);
    ESS_soc(:,k+1)=ESS(:,7)./ESS(:,6);

ESS_cost(:,k)=Gamma*(ESS(:,3).*ESS_P(:,k).*ESS_P(:,k)+ESS(:,4).*abs(ESS_P
(:,k))+ESS(:,5));
    der(:,k)=(1+sign(deltaP_tot)*1.5*(0.5-
ESS_soc(:,k))).*(2*ESS(:,3).*ESS_P(:,k)+ESS(:,4));

%     potsabs(k)=sum(ESS_P(:,k));
%     pots(k)=sum(ESS_P(:,k))-sum(ESS_P(:,1));
%     potsdelta(k)=sum(ESS_P(:,k))-sum(ESS_P(:,k-1));

end

ESS_P;
ESS_soc;

%Cost calculation
```

```
cost=0;
total_cost=zeros(1,end_time);
```

## AUXILIARY FILE: LAGRANGIAN

```
function DeltaP=Lagrangian(Alpha,Const,deltaP_tot,unlim_areas)

Const(unlim_areas+1)=0;

Alpha_c=zeros(unlim_areas,unlim_areas);
Const_c=zeros(unlim_areas,1);
Lamda_c=zeros(unlim_areas,1);

for i=2:unlim_areas

    Alpha_c(i-1,:)=Alpha(1,:)-Alpha(i,:);
    Const_c(i-1,:)=Const(1,:)-Const(i,:);

end

Alpha_c(unlim_areas,:)=ones;
Lamda_c(unlim_areas)=deltaP_tot;

DeltaP=Alpha_c\(Lamda_c-Const_c);
```

# Annex C ANOTHER APPROACH TO THE INFLUENCE OF OTHER AREAS – WARD EQUIVALENT

## CONCEPT

This method was used as the first solution to the issue regarding the influence of "the rest of the world" on the LF of a particular area. It is based on making an equivalent of the rest of the system, the external system, which will be substituted by an injection of power at the boundary buses as in Figure 18. This injection of power will take into account the loads and generators of the external system, but also the influence of the losses in the transmission lines.

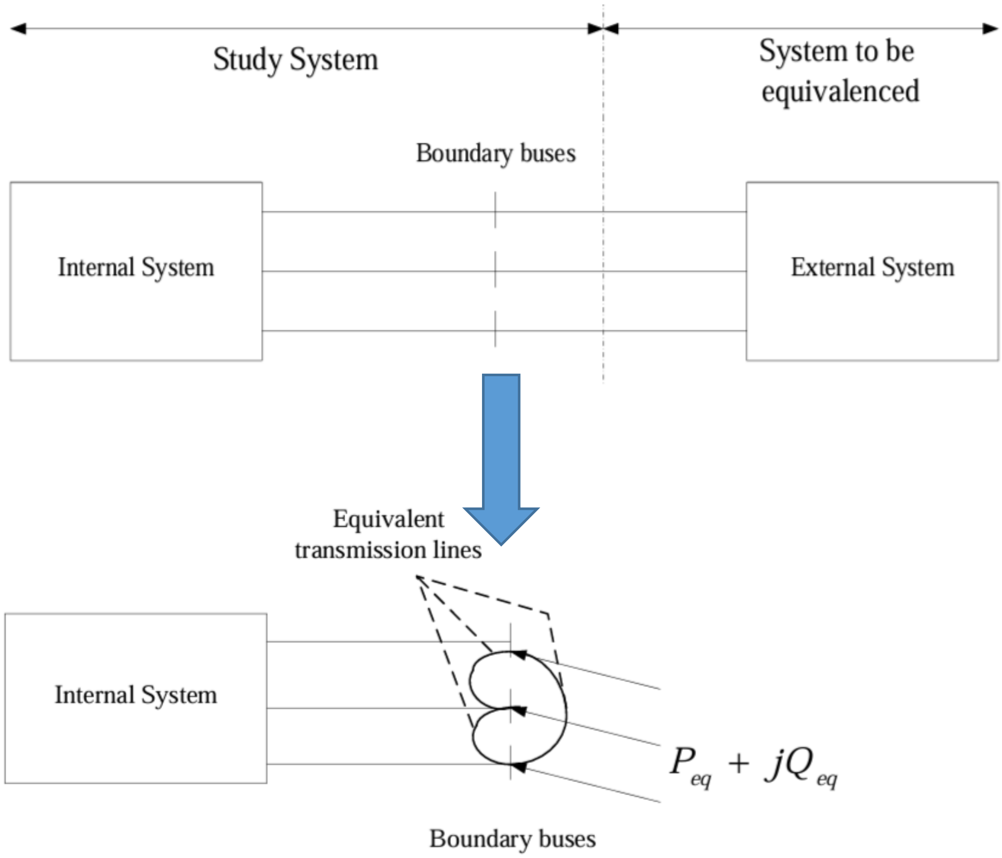

*Figure 18. Ward Equivalent principle*

For such task, it is necessary to introduce some fictive boundary buses which will connect the areas. That way, no connection between internal and external buses will be done but through these boundary buses, leaving the terms of the $Y_{BUS}$ connecting the internal and external buses equal to zero. Then, the system will be reduced from three dimensions (internal, boundary and external) to two (internal and boundary) following the process explained in [4].

## ISSUES

The method was implemented for the 13-bus system from Figure 10. At first, the results were acceptable. However, the selection of the slack bus for each area strongly influenced the results obtained discouraging the use of such method. Especially, when applied with the slack buses that correspond to ESS' locations, results were unacceptable by all means.

Several methods were approached in order to tackle the issue of the slack bus selection and improve the performance of the Ward Equivalent method. The main approaches discussed and implemented were the distributed slack buses method from [6] and the link between the voltage of a certain area's slack bus to the one of the boundary bus obtained in the previous areas.

Nevertheless, none of the solutions arrived at the desired output of giving an appropriate equivalent of the external system. Accordingly, an alternative to the Ward Equivalent was searched until the decomposition method brought the expected results.

# Annex D DECOMPOSITION METHOD – MATLAB CODE

## MAIN FILE

```
%%
clear all
close all
clc

%% input data

% select your system
sys = {'Define your system (Number of buses): '};
title3 = 'Enter numbers of system buses:';
select_system = inputdlg(sys);
system= str2num(select_system{1});

% [msg, id] = lastwarn;
% warning('off', id)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% find the data related to the selected system.
if system==13
    % load profiles:
    load S_loads_13BUS   % it loads "P_loads" and "Q_loads" . These data
are for just one day with 96 sample (each 15 min). The first column is
related to the number of buses.
                         % first Column: No of buses
                         % Second column: kind of buses =>  "1" stands
for residential ; "2" stands for commercial ; "3" stands for industrial
    % line data
    T = readtable('LineData_13BUS.xlsx','ReadRowNames',false);
    % general data
    Sb=5e6;
    StCap=[0.3;0.3;0.3];
    StLoc=[4,6,12];
    StNo=size(StCap,1); %Number of storage
    PVCap=[0;0;0;6;0;0;0;8;0;5;0;0;0];
    Emin=0.2;
    Emax=0.8;
    Ebat_init=[0.3;0.3;0.3]; % initial SoC
end

if system==123
    % load profiles:
    load S_loads_123BUS1   % it loads "P_loads" and "Q_loads" . These
data are for just one day with 96 sample (each 15 min). The first column
is related to the number of buses.
```

```
                           % first Column: No of buses
                           % Second column: kind of buses =>  "1" stands
for residential ; "2" stands for commercial ; "3" stands for industrial
    % line data
    T = readtable('LineData_123BUS.xlsx','ReadRowNames',false);
    % general data
    Sb=7e6;
    StCap=[0.3;0.3;0.3;0.3;0.3];
    StLoc=[6,27,71,98,121];
    StLoc_rel=[6,8,11,19,19];
    StNo=size(StCap,1); %Number of storage
    PVCap=zeros(123,1);

PVCap(3,1)=2;PVCap(12,1)=2;PVCap(22,1)=2;PVCap(33,1)=1;PVCap(45,1)=2;PVCa
p(63,1)=2;PVCap(76,1)=2;PVCap(93,1)=2;PVCap(104,1)=2;PVCap(122,1)=2;
    Emin=0.2;
    Emax=0.8;
    Ebat_init=[0.3;0.3;0.3;0.3;0.3;0.3;0.3;0.3;0.3;0.3;0.3]; % initial
SoC

    connexions=[1 2 15 20 15 1;
                1 3 58 61 23 1;
                3 4 73 78 13 1;
                3 5 99 103 18 1];
    [connexions_No,x]=size(connexions);
    x=[];

end

if system==34
    load S_loads_34BUS_new
    % line data
    T = readtable('LineData_34BUS_new.xlsx','ReadRowNames',false);
    % general data
    Sb=2.5e6;
    Emin=0.2;
    Emax=0.8;
    StCap=[0.3;0.3];
    StLoc=[22,34];
    StNo=size(StCap,1);  %Number of storage
    Ebat_init=[0.3;0.3]; % initial SoC
end
if system==6
    load test6_area1
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% definition of Variables
linedata=zeros([],[]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% line data
CC = table2cell(T);
```

```
for k=1:2
    linedata(:,k)= cell2mat(CC(:,k));%line definition with the buses it
links
end

for k=3:4
    for n=1:size(linedata(:,1),1)
        linedata(n,k)=str2num(CC{n,k});%line definition with the z_pu and
y_pu
    end
end

n_line=length(linedata(:,1));
n_node=max(max(linedata(:,1)),max(linedata(:,2)));


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% define areas

load areaInit_PLF_123_5ESS%areaInit defines the area to which it belongs

No_areas=StNo; % number of areas is equal to the number of ESSs

% define the buses in each area
Area_buses=cell(1,No_areas);

for area=1:No_areas
    buss=[];
    f=1;
    for h=1:n_node
        if StLoc(area)==areaInit(2,h)
            buss(f)=areaInit(1,h);
            f=f+1;
        end
    end
    Area_buses{1,area}=buss;%defines structure with n_area categories and
in each one, the buses that belong to the area are stored
end

load Linedata_area_123_5ESS;%adds linedata_area=all the data of lines in
an area and line_node=# of lines and # of nodes
Ybus_area=cell(1,No_areas);  %% Ybus for all areas


for area=1:No_areas
    Ybus=[];
    linedara_target=Linedata_area{1,area};
    node_line_target=line_node{1,area};
    n_node_area=node_line_target(1,1);
    n_line_area=node_line_target(2,1);
    [Ybus,absY,angleY]=YBUS(linedara_target,n_node_area,n_line_area);
    Ybus( :, ~any(Ybus,1) ) = [];  %delete zero columns
```

```
    Ybus( ~any(Ybus,2), : ) = [];  %delete zero rows
    Ybus_area{1,area}=Ybus;
end

linedara_full=linedata;
n_node_full=n_line;
n_line_full=n_node;
[Ybus,absY,angleY]=YBUS(linedara_full,n_node_full,n_line_full);
Ybus( :, ~any(Ybus,1) ) = [];  %delete zero columns
Ybus( ~any(Ybus,2), : ) = [];  %delete zero rows
Ybus_full=Ybus;

% define the loads for each time step in each area
Area_S=cell(1,No_areas);

for area=1:No_areas

    powers=[];

    nodes_area=Area_buses{1,area};
    n_nodes_area=length(nodes_area);

    for i=1:n_nodes_area

        node=nodes_area(i);
        powers(i,:)=-P_loads(node,:)-1i*Q_loads(node,:);%Defined negative
as loads

    end

    powers(:,1)=[];
    powers(:,2)=[];
    Area_S{1,area}=powers;

end

S_full=-P_loads(node,:)-1i*Q_loads(node,:);
S_full(:,1)=[];
S_full(:,2)=[];

% define the initial voltage. At this point, all set to 1. However, this
% must be changed to the real values
Area_volt_init=cell(1,No_areas);

for area=1:No_areas

    Area_volt=[];

    nodes_area=Area_buses{1,area};
    n_nodes_area=length(nodes_area);
```

```
    Area_volt=ones(n_nodes_area,1);

    Area_volt_init{1,area}=Area_volt;

end

Area_Sstar=cell(1,No_areas);
Vbus_all=cell(1,No_areas);

Sstar_all_full=(4*S_full/Sb);

for area=1:No_areas

    S_all_area=Area_S{1,area};
    Sstar_area=(4*S_all_area/Sb);%+PV(hk)*PVCap_area1*1.1*0.00039;
    Area_Sstar{1,area}=Sstar_area;

end
%
% for hk=1:96
%
%     Ybus=Ybus_full;
%     absY_full=abs(Ybus);
%     angleY_full=angle(Ybus);
%
%     Sstar_full=Sstar_all_full(:,hk);
%
%     slack_full=1;
%     v_slack_full=1;
%     absE_full=v_slack_full*ones(n_node,1);
%     angleE_full=zeros(n_node,1);
%
%     for k=1:100
%
Efull=[absE_full.*cos(angleE_full)+1i*absE_full.*sin(angleE_full)];
%         Ifull=Ybus*Efull;
%         Sfull=(Efull.'.*Ifull').';
%         DeltaSfull=Sstar_full-Sfull;
%         DeltaSfull(slack_full)=[];
%         deltaSfull=[real(DeltaSfull);imag(DeltaSfull)];
%         if max(abs(deltaSfull))<0.01
%             break
%         end
%
[absE_full,angleE_full,J]=itera(absE_full,angleE_full,absY_full,angleY_fu
ll,deltaSfull,n_node,slack_full);
%     end
%
%     Vbus_full(:,hk)=absE_full;
%
% end
```

```
for hk=1:96

    prevP_all=zeros(connexions_No,1);
    deltaP_all=zeros(connexions_No,1);
    prevQ_all=zeros(connexions_No,1);
    deltaQ_all=zeros(connexions_No,1);

    for iter=1:100

        for area=1:No_areas

            %Loading info from area
            Ybus=Ybus_area{1,area};
            absY_area=abs(Ybus);
            angleY_area=angle(Ybus);
            nodes_area=Area_buses{1,area};
            n_nodes_area=length(nodes_area);
            slack_area=StLoc_rel(area);
            Sstar_area_all=Area_Sstar{1,area};
            Sstar_area=Sstar_area_all(:,hk);

            v_slack_area=1;
            absE_area=v_slack_area*ones(n_nodes_area,1);
            angleE_area=zeros(n_nodes_area,1);

            for k=1:100

Earea=[absE_area.*cos(angleE_area)+1i*absE_area.*sin(angleE_area)];
                Iarea=Ybus*Earea;
                Sarea=(Earea.'.*Iarea').';
                DeltaSarea=Sstar_area-Sarea;
                DeltaSarea(slack_area)=[];
                deltaSarea=[real(DeltaSarea);imag(DeltaSarea)];
                if max(abs(deltaSarea))<0.01
                    break
                end

[absE_area,angleE_area,J]=itera(absE_area,angleE_area,absY_area,angleY_ar
ea,deltaSarea,n_nodes_area,slack_area);
            end
        Vbus_area{1,area}=Earea;

        end

        for j=1:connexions_No

            Area_b1=connexions(j,1);
            Area_b2=connexions(j,2);

            bus_b1=connexions(j,5);
            bus_b2=connexions(j,6);
```

```
            abs_bus_b1=connexions(j,3);
            abs_bus_b2=connexions(j,4);

            Sstar_area_all1=Area_Sstar{1,Area_b1};
            Sstar_area_all2=Area_Sstar{1,Area_b2};

            Vbus_area1=Vbus_area{1,Area_b1};
            Vbus_area2=Vbus_area{1,Area_b2};

            Vbus_b1=Vbus_area1(bus_b1);
            Vbus_b2=Vbus_area2(bus_b2);

            abs_Vbus_b1=abs(Vbus_b1);
            abs_Vbus_b2=abs(Vbus_b2);

            angle_Vbus_b1=angle(Vbus_b1);
            angle_Vbus_b2=angle(Vbus_b2);

            prevP_tie=prevP_all(j);
            prevQ_tie=prevQ_all(j);

            P_tie=abs_Vbus_b1^2*real(Ybus_full(abs_bus_b1,abs_bus_b2))-
abs_Vbus_b1*abs_Vbus_b2*real(Ybus_full(abs_bus_b1,abs_bus_b2))*cos(angle_
Vbus_b1-angle_Vbus_b2)-
abs_Vbus_b1*abs_Vbus_b2*imag(Ybus_full(abs_bus_b1,abs_bus_b2))*cos(angle_
Vbus_b1-angle_Vbus_b2);
            Q_tie=-
abs_Vbus_b1^2*imag(Ybus_full(abs_bus_b1,abs_bus_b2))+abs_Vbus_b1*abs_Vbus
_b2*imag(Ybus_full(abs_bus_b1,abs_bus_b2))*cos(angle_Vbus_b1-
angle_Vbus_b2)-
abs_Vbus_b1*abs_Vbus_b2*real(Ybus_full(abs_bus_b1,abs_bus_b2))*cos(angle_
Vbus_b1-angle_Vbus_b2);

            deltaP_tie=P_tie-prevP_tie;
            deltaQ_tie=Q_tie-prevQ_tie;

            deltaP_all(j)=deltaP_tie;
            prevP_all(j)=P_tie;
            deltaQ_all(j)=deltaQ_tie;
            prevQ_all(j)=Q_tie;


Sstar_area_all1(bus_b1,hk)=Sstar_area_all1(bus_b1,hk)+deltaP_tie+deltaQ_t
ie;
            Sstar_area_all2(bus_b2,hk)=Sstar_area_all2(bus_b2,hk)-
deltaP_tie-deltaQ_tie;

            Area_Sstar{Area_b1,area};Sstar_area_all1;
            Area_Sstar{Area_b2,area}=Sstar_area_all2;

        end
```

```
        if max(abs(deltaP_all))<0.01
            break
        end

    end

    for area=1:No_areas;

        Vbus_all_area=Vbus_all{1,area};
        Vbus_all_area(:,hk)=Vbus_area{1,area};
        Vbus_all{1,area}=Vbus_all_area;

    end

end
```

## AUXILIARY FILE: ITERA

```
function [Eabs,Eangle,J]=itera(Eabs,Eangle,Yabs,Yangle,DeltaS,n_nodi,s)
global J;
for ki=1:n_nodi%Uses Newton-Raphson's method
    %Contribution to Jacobian by the same bus

dPdEabs(ki,ki)=2*Yabs(ki,ki)*Eabs(ki)*cos(Yangle(ki,ki));%????????????Wh
y the 2*
    dPdEangle(ki,ki)=0;
    dQdEabs(ki,ki)=-
2*Yabs(ki,ki)*Eabs(ki)*sin(Yangle(ki,ki));%????????????Why the 2*
    dQdEangle(ki,ki)=0;
    for kh=1:n_nodi
        if kh~=ki
            %Contribution of the other buses

dPdEabs(ki,ki)=dPdEabs(ki,ki)+Yabs(ki,kh)*Eabs(kh)*cos(Eangle(ki)-
Eangle(kh)-Yangle(ki,kh));
            dPdEabs(ki,kh)=Yabs(ki,kh)*Eabs(ki)*cos(Eangle(ki)-
Eangle(kh)-Yangle(ki,kh));
            dPdEangle(ki,ki)=dPdEangle(ki,ki)-
Eabs(ki)*Yabs(ki,kh)*Eabs(kh)*sin(Eangle(ki)-Eangle(kh)-Yangle(ki,kh));

dPdEangle(ki,kh)=Yabs(ki,kh)*Eabs(ki)*Eabs(kh)*sin(Eangle(ki)-Eangle(kh)-
Yangle(ki,kh));

dQdEabs(ki,ki)=dQdEabs(ki,ki)+Yabs(ki,kh)*Eabs(kh)*sin(Eangle(ki)-
Eangle(kh)-Yangle(ki,kh));
            dQdEabs(ki,kh)=Yabs(ki,kh)*Eabs(ki)*sin(Eangle(ki)-
Eangle(kh)-Yangle(ki,kh));
```

```
dQdEangle(ki,ki)=dQdEangle(ki,ki)+Eabs(ki)*Yabs(ki,kh)*Eabs(kh)*cos(Eangl
e(ki)-Eangle(kh)-Yangle(ki,kh));
            dQdEangle(ki,kh)=-
Yabs(ki,kh)*Eabs(ki)*Eabs(kh)*cos(Eangle(ki)-Eangle(kh)-Yangle(ki,kh));
        end
    end
end

% Eliminating data from the slack bus
dPdEabs(:,s)=[];
dPdEangle(:,s)=[];
dQdEabs(:,s)=[];
dQdEangle(:,s)=[];

% Eliminating data from the slack bus
dPdEabs(s,:)=[];
dPdEangle(s,:)=[];
dQdEabs(s,:)=[];
dQdEangle(s,:)=[];

%Composing the complete Jacobian matrix (Book pages 335 and around)
J=[dPdEabs,dPdEangle;dQdEabs,dQdEangle];
%x is array of increments of voltage and angle to each bus
x=J\(DeltaS);%Like making DeltaS/J
xx=x(n_nodi:2*(n_nodi-1));%Separate and stores angles in xx. Those
indexes are due to the elimination of slack bus rows
x2(1:s-1,1)=x(1:s-1);%???????????????????????????????Isn't this wrong?
Shouldn't it be n_nodi where s
xx2(1:s-1,1)=xx(1:s-1);%???????????????????????????????Isn't this wrong?
Shouldn't it be n_nodi where s
x2(s,1)=0;%Eliminating data from the slack bus
xx2(s,1)=0;%Eliminating data from the slack bus
x2(s+1:n_nodi,1)=x(s:n_nodi-1);%???????????????????????Isn't this wrong?
Shouldn't these two lines go before the previours 2
xx2(s+1:n_nodi,1)=xx(s:n_nodi-1);%???????????????????????Isn't this
wrong? Shouldn't these two lines go before the previours 2
Eabs=Eabs+x2;%Add the increment of voltage magnitude
Eangle=Eangle+xx2;%Add the increment of voltage angle
% mmmm=1;
```

## AUXILIARY FILE: YBUS

```
function [Ybus,absY,angleY]=YBUS(linedata,n_node,n_line)

y_ih=1./linedata(:,3);          %ammettenze longitudinali
y_i_ih=zeros(n_node,n_node);    %matrice in cui alla i-esima riga e j-
esima colonna  l'ammettenza trasversale/2 della linea tra i nodi i e j
% absy_ih=abs(y_ih);
% angley_ih=angle(y_ih);
% g_ih=real(y_ih);
```

```
% b_ih=imag(y_ih);

for k=1:n_line
    y_i_ih(linedata(k,1),linedata(k,2))=linedata(k,4)/2;
    y_i_ih(linedata(k,2),linedata(k,1))=linedata(k,4)/2;
end
for k=1:n_node
    y_i(k)=sum(y_i_ih(k,:));        %l'i-esimo elemento ? la somma delle 
ammettenze trasversali dei rami connessi al nodo i
end
% g_i_ih=real(y_i_ih);
% b_i_ih=imag(y_i_ih);

Yp=diag([y_ih.',y_i]);  %matrice primitiva

A=zeros(n_line+n_node,n_node); %matrice incidenza nodi-lati

for k=1:n_line
    A(k,linedata(k,1))=1;
    A(k,linedata(k,2))=-1;
end
for k=1:n_node
    A(n_line+k,k)=1;
end
Ybus=A.'*Yp*A;
absY=abs(Ybus);
angleY=angle(Ybus);
```