ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

# IMPACTO DE MECANISMOS DE PREDICCIÓN DE GENERACIÓN FOTOVOLTAICA EN EL SISTEMA ELÉCTRICO


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Madrid

Julio 2014

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**IMPACTO DE MECANISMOS DE PREDICCIÓN DE GENERACIÓN FOTOVOLTAICA EN EL SISTEMA ELÉCTRICO**

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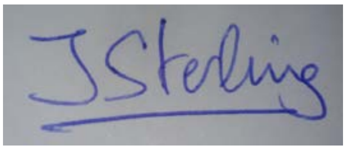

Fdo: Javier Sterling

# Impacto de mecanismos de predicción de generación fotovoltaica en el sistema eléctrico

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## RESUMEN

A escala europea hay una tendencia de integración de energías renovables en la red de distribución eléctrica, típicamente conectadas como generación distribuida (GD). Una de las tecnologías más comunes es la fotovoltaica (FV). Alguna de sus ventajas son la conciencia ambiental, la progresión tecnológica y la fiabilidad.

La generación distribuida ha aumentado desde unos 4GW de potencia instalada total en 2003 hasta cerca de 128GW en 2013. Varios estudios señalan la tendencia al crecimiento de la GD para los próximos años, y tendrá un papel importante en los sistemas eléctricos de potencia (EPRI, 2014).
Este proyecto pretende satisfacer los siguientes objetivos:

- Analizar una red rural para identificar los problemas asociados a altos niveles de penetración FV.
- Sugerir soluciones factibles para esos problemas
- Evaluar indicadores clave del rendimiento (KPI) para cada variable problemática con cada solución (pérdidas, niveles de tensión) que puedan ayudar a decidir entre las diferentes opciones que pueda tener el operador del sistema.
- Realizar una valoración económica asociada a esos indicadores.

- Analizar el impacto de la predicción de generación FV en una red rural.

En generación distribuida, hay un impacto relevante sobre las pérdidas. (Mutale et al., 2000) analizan este efecto. Ante baja penetración, las pérdidas frecuentemente se ven reducidas porque la distancia al alimentador es menor, y parte de la energía necesaria proviene de nudos de generación cercanos al consumo. Si hay un nivel de alta penetración, el flujo de potencia puede invertirse (exportando energía a la red). Para casos de muy alta penetración, las pérdidas podrían ser incluso mayores que en un caso sin generación (L. González et al, 2011).

Entre las posibles soluciones para soportar altos niveles de penetración (NREL,2013) propone, de menos a más crítico:

1. Ajustar los reguladores de tensión para estabilizar los niveles de tensión
2. Los inversores serán configurados para absorber gradualmente potencia reactiva.
3. Notificar al operador del sistema de desconexión parcial o total del sistema de generación fotovoltaica

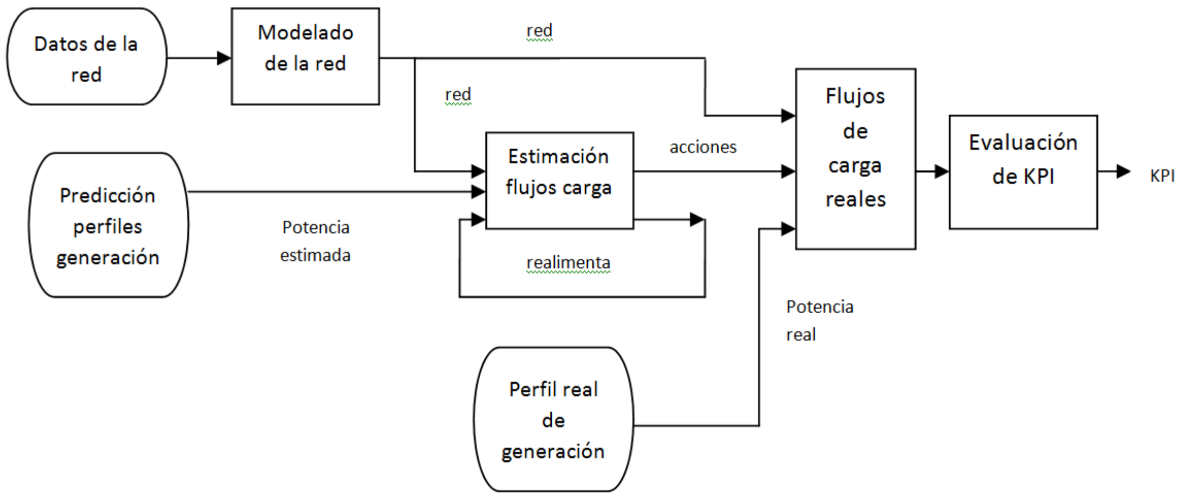
Este proyecto estudia el efecto sobre pérdidas y niveles de tensión de un transformador con cambiador de tomas en carga (1.) para ciertos perfiles de consumo y curvas reales de generación fotovoltaica obtenidas del tejado del IIT, Madrid, España, que han sido escalados para estudiar el efecto de un sistema con alta densidad de paneles. Si el transformador no solucionara los problemas de tensión, los inversores de las unidades FV serían configuradas para absorber potencia reactiva (2.). Tratando de reducir pérdidas, algunos condensadores se sitúan en la red. Afortunadamente, no se tuvo que desconectar generadores (3.) para solucionar los problemas.

Hay un claro impacto del error de predicción. Cuanto más cercano sea el perfil de generación al perfil real, con mayor facilidad las acciones de control solucionan los problemas. Tener un error grande de predicción puede tener consecuencias negativas para la red, o al menos para la planificación operacional. Esto sugiere que puede merecer la pena investigar en métodos de predicción para aumentar su precisión.

De los resultados, algunas conclusiones para el nivel de penetración impuesto son expuestas. Si no se aplican medidas de control, la calidad de las tensiones es inaceptable. La equivalencia económica de la baja calidad de servicio en cuanto a tensiones es considerablemente grande. Esto sugiere atención especial para cada diseño considerando altos niveles de penetración, e investigación de las soluciones óptimas para cada caso teniendo en cuenta acciones de control a largo plazo.

Los datos de entrada llevan al modelado de la red, que es el primer paso. Con perfiles de generación (normalmente de predicción) y datos de la red, flujos de carga (FC) se llevan a cabo. Los resultados de estos flujos de carga son resultados para una predicción y en el primer caso no se tomarán acciones de control. En este proyecto se realiza un flujo de carga por cada hora, y si no cubre los resultados esperados (p.e. requerimientos de tensión), una realimentación permite cambiar las acciones de control. Una vez las acciones de control para resolver los problemas son decididas (individualmente para cada perfil), el "Flujo de cargas real" es obtenido con datos de la red y el perfil real de generación FV. Se hace notar que el perfil real puede diferir de los perfiles de predicción, y este efecto se muestra en esta etapa. Estos datos del "Flujo de cargas real" tienen perfiles para cada nudo de tensión y perfiles de potencia global. Permiten observar el impacto de la predicción y el impacto de alta penetración de FV en redes rurales. Al final del proceso, las variables principales (KPI) y su valoración económica son obtenidos.

En este proyecto, tres escenarios de predicción serán introducidos en el software. Escenario moderado significa que la generación real es ligeramente menor que la predicción. Escenario de sobre-predicción es cuando la predicción es claramente mayor que el perfil real, y sub-predicción cuando la predicción es mayor que el perfil real. Esta metodología es resumida en la siguiente Figura:




Una parte importante es el estudio del impacto de la predicción. Basándose en la información que la herramienta de predicción manda, con cierta antelación perfiles de predicción son creados. Estos llevan a perfiles estimados de generación. Para cada uno de ellos, hay diferentes posibilidades de acciones de control (p.e. cambiar la toma del transformador). La mejora acción de control (p.ej la mejor toma) es seleccionada para cada tipo de acción de control.

Para analizar los datos, los resultados del Power Factory han sido exportados como archivos separados por comas. En ese formato se han enviado a Microsoft Excel©, con referencias cruzadas en una organización automática de archivos, incluyendo archivos con representaciones gráficas para cada caso de estudio. Estos datos son analizados y posibles soluciones son sugeridas.

La herramienta principal para modelar la red y calcular flujos de caga ha sido DigSILENT Power Factory ©. Es un software para simulación de sistemas eléctricos. Cubre sistemas de distribución, generación y transporte de energía eléctrica. Es difícil de aprender pero intuitivo si se requieren tareas básicas. Permite manejar todas las variables con un concepto de base de datos única, que es a su vez flexible.

La red analizada es rural. Hay largas distancias entre los puntos de consumo y entre el transformador y cada nudo. Esto afectará a variables del sistema de una manera específica y diferente a como sería en una red rural. Este sistema está conectado a una red de nivel superior de tensión [0,4-15] kV que eventualmente conectará con la red de media tensión.

## ABSTRACT

In European scale there is an increasing amount of renewable energy to be integrated in the electricity distribution network, typically connected as Distributed Generation (DG). One of the most common technologies is photovoltaic (PV). Some of its remarkable advantages are environmental consciousness, technological progression and reliability.

Distributed PV power generation has increased from approximately 4 GW of global installed capacity in 2003 to nearly 128 GW in 2013. Several studies point out the tendency towards growing of DG for the next years, and it will take an important role in the electric power systems (EPRI, 2014).

This final degree Project is meant to solve the following objectives:

- Analyze a rural network to identify the problems related to a high PV penetration levels.
- Suggest feasible solutions for those problems.
- Evaluate Key Performance Indicators (KPI) for the main problematic variables for every solution (losses, voltage over-under levels) that may help to decide among the different options that the distribution network operator may have.
- Make an economic valuation related to the KPI and losses.
- Analyze the impact of PV generation forecast in a rural network.

In distributed generation, there is a relevant impact on losses. (Mutale, et al., 2000) analyze this effect. With low penetration, losses are usually reduced, because distance from feeder is reduced, and part of the energy needed comes from generation nodes, closer to consumption. If there is a high penetration scenario, flow can be inverted (energy exported to the network). For very high penetration scenarios, losses could even be greater than in a case with no generation. (L.González et al, 2011).

Among possible solutions to bear high PV penetration levels (NREL, 2013) suggest, from least to most critical:

1. Adjust the voltage regulators to stabilize the voltage levels.
2. The inverters will be configured to absorb reactive power gradually.
3. Notify the system operator to disconnect all or part of the PV system.

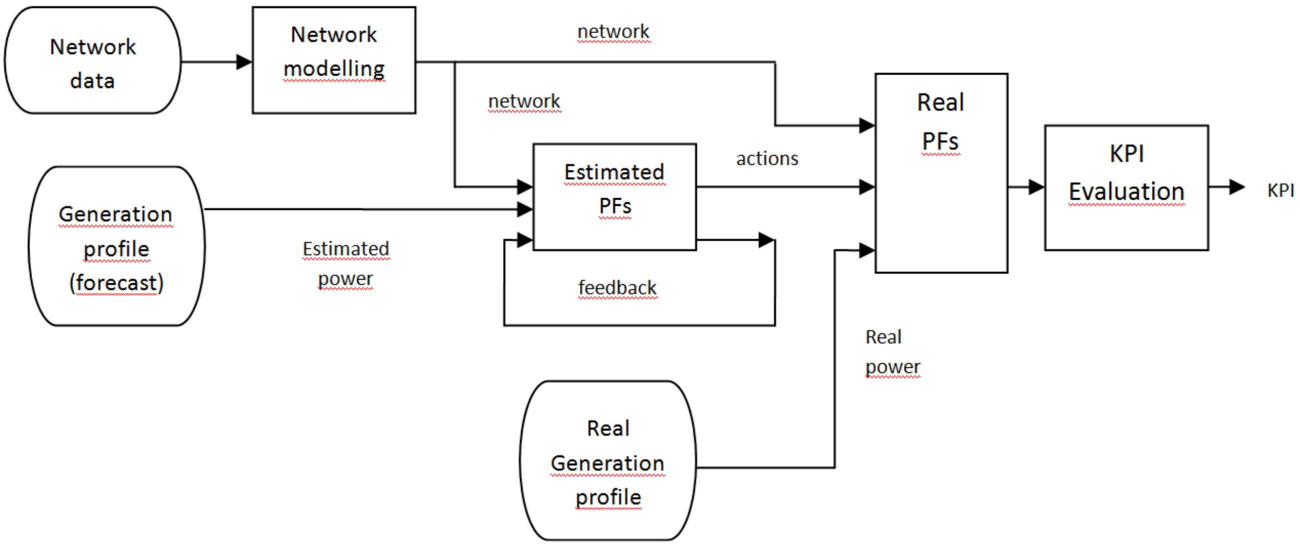
This project studies the effect on losses and voltage levels of an on load tap transformer (1.) for certain consumption profiles and real generation profiles obtained from the rooftops of the IIT, in Madrid, Spain that have been scaled to study the effect on a highly penetrated system. If the transformer does not solve voltage problems, the inverters of the PV units will be configured to absorb reactive power (2.). Attempting to reduce losses, some capacitors will be also placed. Fortunately, curtailment (3.) was not a necessary condition to solve the problems.

The network that will be analyzed is rural. There are large distances among consumption points and also considerable distances between the transformer and each node. This will affect several variables in a specific and different way that an urban network. This system is connected to an upper voltage level through a transformer of [0,4-15] kV that will eventually connect to the medium voltage network. The main tool to model the network and to execute scripts that have calculated load flows and Time Sweep Analysis has been DigSILENT Power Factory ©. It is software for electric system simulation. It covers distribution, generation and transmission industrial systems, integrated, hard to learn but intuitive if only basic tasks are requested. It allows managing all variables with a unique database concept, which is also flexible.

To analyze the data, the results from Power Factory have been exported as comma separated values files. In that format the data is sent to Microsoft Excel ©, cross-referenced in an automatic file organization, including the files with the data plot for every case study. This data is examined and possible solutions are suggested.

An important part is the study of the impact of forecasting. Based on the info that the forecasting tool sends, certain time ahead several forecast generation profiles are created. This forecast profiles lead to estimated generation profiles. For each of them, there are different type of possible control actions (e.g. changing tap transformer). The best control action (e.g. the optimal tap) is selected for each type of control action.

In this project, three forecast cases will be introduced into the software. Moderate scenario means that the actual generation is a slightly lower that the forecast. Overcast when generation is much lower than expected and undercast when generation is higher than forecast. For each of these three forecast cases, there are three different profiles: two forecasts (the day ahead forecast and fifteen minutes ahead updating the data every hour) and the actual profile for the specific day. The methodology is summarized in the following Figure:




Input data leads to network modeling, which is the first step. With a generation profile (normally forecast) and data from the network, power flows (PFs) can be executed. The results of those power flows are network results for a forecast scenario with no control measures applied. In this project one power flow per hour will take place, and if it did not cover the expected results (e.g. voltage over requirement limits), a feedback allows changing control actions. Once the control actions to solve the problems are decided (individually for every profile) the "Real power flow" is obtained with network data and actual PV generation. Note that the actual generation profile may differ from the forecast profile, and that effect is noticed in this stage, This "Real power flow" data has voltage profiles for every node and power profiles for the system. It allows observing the impact on forecasting and the impact of high PV penetration systems. In the end of the process, the main variables and economic valuation (KPIs) are examined.

From the results, some conclusions for the penetration level imposed are exposed. If no control measures are applied, the voltage quality is unacceptable. The economic translation of low quality voltage provided is considerably large. This suggests specific focus on every design considering high PV penetration levels, and investigation of the optimal solutions for every case regarding control actions in the long term.

There is a clear impact of the forecast error. The closer the forecast is to reality, the better the control techniques solve the problems. Having a very big forecast error might have negative consequences to the network, or at least to the operational planning.  This suggests that investigation on forecast methods to increase its accuracy might be worthwhile.

Gracias a la U.P. Comillas por esta oportunidad, al IIT y los directores por los medios y el tiempo dedicado, a mi familia por apoyarme, y particularmente a María y mi madre por aguantarme.

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# Chapter 1 INTRODUCTION

In the beginning of electricity generation there were small generators of Direct Current (DC) that were very close to consumption centers.

Due to the AC development and transformers arising voltage, it became possible to transfer higher energies to longer distance with less losses produced by Joule Effect.

During the last centuries, the electric power systems have been designed to generate mostly in Alternate Current (AC) in high energy content and send the energy through transmission systems to lower energy levels where consumers receive it. Most of the electric power systems are designed radially, where energy flows in one direction, from generation to consumption. For high and very high voltage levels, there is a mesh design. At medium voltage levels it shows a mesh layout, whereas it is exploited radially. At lower voltage levels it can be found a radial arrangement.

Traditionally the electric power systems have been designed and operated following a hierarchical framework in which big generator groups can be found in higher levels. The energy transformed there is transported to the big consumption centers thanks to the very high voltage lines (V>145kV). This energy will be converted thanks to the transformers into lower levels (36kV<V≤145kV) before reaching distribution transformer centers at medium voltage (1<V≤36kV). The energy will finally be transformed at low voltage levels (V≤1kV) where it will be consumed by final users or clients.

In this scheme energy flows from higher voltage levels to lower voltage levels. In Figure 1 it is shown a representation of the structure.

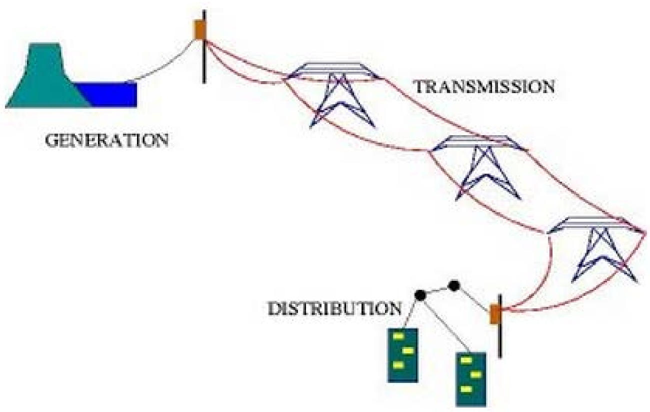



Figure 1: Classical one-way power flow

This structure shows several advantages, and some of them are pointed out:

*Efficiency of big generator groups*. Compared to small generator units, size is in favor of big generator plants. (Willis and Scott, 2000)

*Use of transport network.* Its existence allows transporting big energy quantities producing few losses. The connection between transport networks allows reducing the reserve requirements of the system (Davis, 2000) and when there is a centralized organization, usually the most economical units can be dispatched. Big generator and big transport network capacity add stability to the system (Wheat, 1999).

*Design of distribution networks.* The single one-way power flow allows a more simplified design and operation.

On the other hand, some remarkable disadvantages are:

*Distance among generation and consumption centers*. This usually big distance forces to build expensive transport networks. Also, the greater the distance is, the larger the losses are.

*Environmental pollution and eco-friendly trend.* Big generators produce strong local contamination, which could be displaced by the wind to far locations. Fossil fuels are more expensive every time and there is a clear trend to the use of more eco-friendly technologies.

*System reliability*. In case of problems at higher voltage levels, a lot of elements in lower levels might be affected.

In the recent decades there has been a comeback to the starting point, where small generators produce near consumption centers. This means that the power flow might also move from lower to higher voltage levels.

In European scale there is an increasing amount of energies to be integrated in the electricity distribution network. This is known as Distributed Generation (DG). There are several definitions for this concept, but the one used in this project will be (Mendez, 2005): "*Distributed Generation refers to all the energy sources connected to distribution networks directly connected to them or through the users, with or without the possibility to operate in parallel to the network or in isolated state.*"

A representation of the system including DG is shown in Figure 2.

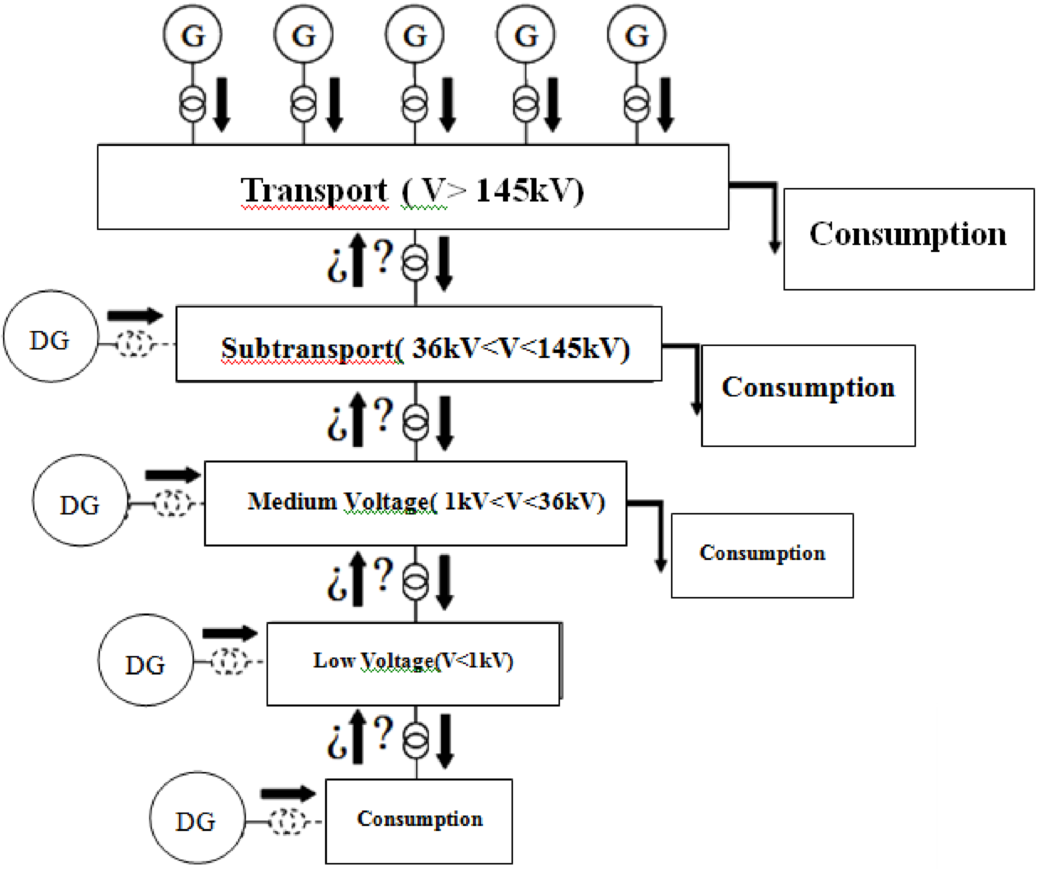



Figure 2: Representation of the electric power system including DG

Some of the remarkable advantages of distributed generation are introduced:

*Environmental consciousness.* DG systems allow the possibility to include directly renewable energies such as solar, wind, biomass or more efficient systems, like CHP. This also helps diversification of energy sources, and a lot of governments have encouraged alternative energies.

*Technological progression. D*emonstrated with several technologies which have reached the market stage and are reducing its prices every year at the same time they increase its efficiency.

*Reliability.* In activities where continuous energy has to be granted, this local production is an additional possibility if there is an interruption of energy flow from higher levels.

Distributed PV power generation has increased from approximately 4 GW of global installed capacity in 2003 to nearly 128 GW in 2013. Several studies point out the tendency towards growing of DG for the next years, and it will take an important role in the electric power systems. (EPRI, 2014)

## *1.1 OBJECTIVES OF THE FINAL DEGREE PROJECT*

This final degree Project is meant to solve the following objectives:

- Analyze a rural network to identify the problems related to a high PV penetration levels.
- Suggest feasible solutions for those problems.
- Evaluate Key Performance Indicators (KPI) for the main problematic variables for every solution (losses, voltage over-under levels, curtail) that may help to decide among the different options that the distribution network operator may have.
- Make an economic valuation related to the KPI.
- Analyze the impact of PV generation forecast in a rural network.

In order to satisfy these objectives, it is necessary to review the technical characteristics of the PV generators and the other network components that can be found detailed on 3.1. Based on those characteristics, generation and consumption profiles, several scenarios and problems will be analyzed and some solutions will be suggested.

The project is intended to be scalable and realistic. With this purpose, it is shown an extreme case of a rural network with long distance among nodes, so for less demanding cases the same profiles could be applied. Also real generation and average consumption profiles have been chosen and are shown across the project.

## *1.2 RESOURCES AND TOOLS*

The main tool to model the network and to execute scripts that have calculated load flows and Time Sweep Analysis has been DigSILENT Power Factory ©.

It is software for electric system simulation. It covers distribution, generation and transmission industrial systems, integrated and easy to use if not very specific tasks are requested. It allows managing all variables with a unique database concept, which is also flexible.

Power Factory has a large amount of variable analysis predefined tools, such as Power flow that computes the particular state of all the elements inside the network for a particular moment, or Time Sweep Analysis that allows daytime results of certain variable through all the requested time.

The license used was a student version, limited to fifty nodes. Note that this project is scalable.

To analyze the data, the results from Power Factory have been exported as comma separated values files. With that format they have been requested by Microsoft Excel ©, cross-referenced in an automatic file organization, including the files with the data plot for every case study.

Real generation profiles and forecast profiles have been used as input data to the process, making it more realistic. Forecast profiles analyze the predicted power taking temperature and radiation as input variables, and predicting power. Measurements of temperature, radiation, DC power and AC power take place in the PV generators. There is certain loss due to the DC/AC conversion, and different profiles have been chosen to do several analysis in Chapter 4 Results.

## *1.3 STATE OF ART*

In this section some suggestions to solve the main problems anticipated in Chapter 1 are shown, individually for every mentioned problem.

### 1.3.1 VOLTAGE LEVELS

There have been many qualitative proposals regarding control methods, and two have been chosen as the most representative.

(Tan, Kirschen, 2007) proposed two techniques to overcome problems that PV penetration may cause: constant power factor control with inverters and automatic voltage control from the inverter.

Regarding constant power factor control, it may be controlled from 0.85 leading to 0.85 lagging. Updated data from manufacturers in some models specify a wider range (0.8 leading to 0.8 lagging). This means that the inverter will absorb reactive power in order to decrease voltage levels when required (leading power factor).

Regarding automatic voltage control from the inverter itself, when voltage reaches a reference level, it activates the control system, reducing or rising the voltage levels via reactive power control.

From another angle, (NREL, 2013) offers a list of possible measures, from least to most critical:

1. Adjust the voltage regulators to stabilize the voltage levels.
2. The inverters will be configured to absorb reactive power gradually.
3. Notify the system operator to disconnect all or part of the PV system.

A common conclusion in both papers is to continue along these lines, and provide more quantitative analysis.

### 1.3.2 LOSSES

In distributed generation, there is a relevant impact on losses. (Mutale, et al., 2000) explain this effect. With low penetration, losses are usually reduced, because distance from feeder is reduced, and part of the energy needed comes from generation nodes, closer to consumption. If there is a high penetration scenario, flow can be inverted (energy exported to the network). For very high penetration scenarios, losses could even be greater than in a case with no generation. (L.González et al, 2011)

(IJACSA, Sep 2010) suggests techniques for optimal capacitor placement, in order to minimize peak power considering the capacitor cost. Capacitors might affect the power flow.

### 1.3.3 IMPACT OF FORECASTING

Quoting (Eisenrich et al., 2010):

> “Standard load profiles are a promising way to investigate the impact of distributed generation systems on an existing grid. With a resolution of 15

> minutes they allow detailed load flow simulations to study the development of characteristic parameters in the course of one day."

Regarding PV generation, in the present days several methods are being tested in order to provide a more accurate forecast, from the radiation point of view. Several experiments are taking place around the world, some of them very innovative, such as forecast via satellite (Espinar-Tarragona, 2010). They are in general immature, and have low accuracy on cloudy days.

## *1.4 STRUCTURE OF THE FINAL DEGREE PROJECT*

In Chapter 1 a global view of the current electric power system has been given, the objectives of this final degree project were defined, and the tools which have been used to analyze and solve different situations were shown. The current state of art was described regarding several problematic variables, and gives rise to the following chapters to solve those problems. Chapter 2 will present an overview of the rural networks, and will introduce some definitions to clarify concepts. Then Chapter 3 will define the technical analysis done to the rural network and the case study modelling modeling, with proposals to solve the problems introduced. Right after, Chapter 4 shows the results of the process, that are displayed and clarified. At last, some conclusions and future developments show up.

# Chapter 2 CASE STUDY DEFINITION AND SCENARIOS

## 2.1 INTRODUCTION

There are several consequences that must be analyzed before the introduction of high proportion of distributed generation, i.e.: losses, stability and network operation, inverted power flow, voltage profiles, service quality, short-circuit power and security. This is a technical challenge for distribution companies.

This analysis will try to show some of the problems and solutions in a steady-state system with high PV penetration.

In this project some of these variables will be analyzed, such as voltage quality, losses and curtail in a high penetrated network in order to drive the distributors into reliable and efficient investments.

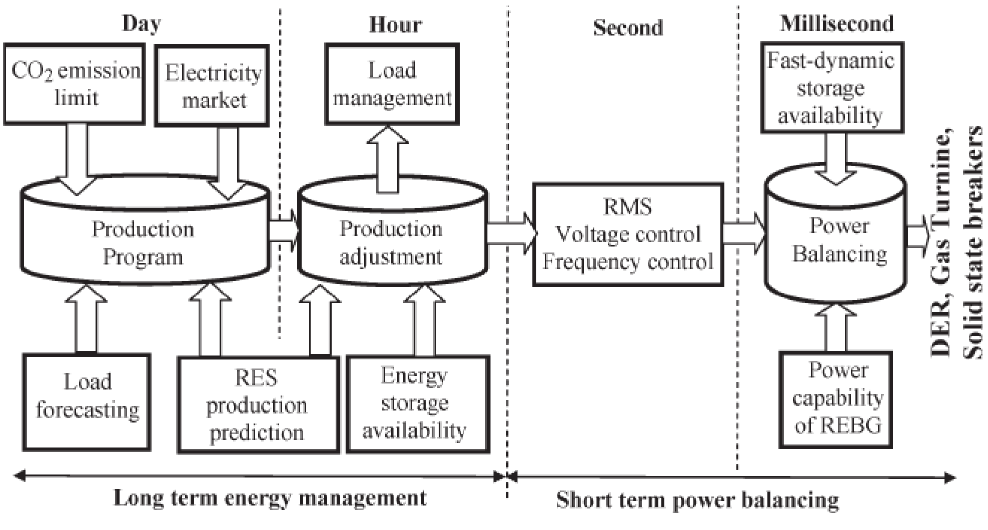



Figure 3: Energy management and power balancing

In Figure 3 the long term energy management and short term power balancing are shown. (Kanchev et al., 2011)

In short term power balancing, frequency and voltage are controlled, at an even faster level power balancing is done.

In relation to long term energy management, there is a production program that in several countries requires forecasts that extent 36 hours ahead, such as the Spanish market, that requires forecast at noon for the following day. This usually depends on the timing of electricity markets and also in weather forecasting. (S. Pelland et al., 2013)

There are also hour ahead forecasts for the intra-daily market in the production adjustment phase, and possible energy storage availability is requested.

This forecasts could be significantly variable. Three of the most important cases are shown in Figure 4.

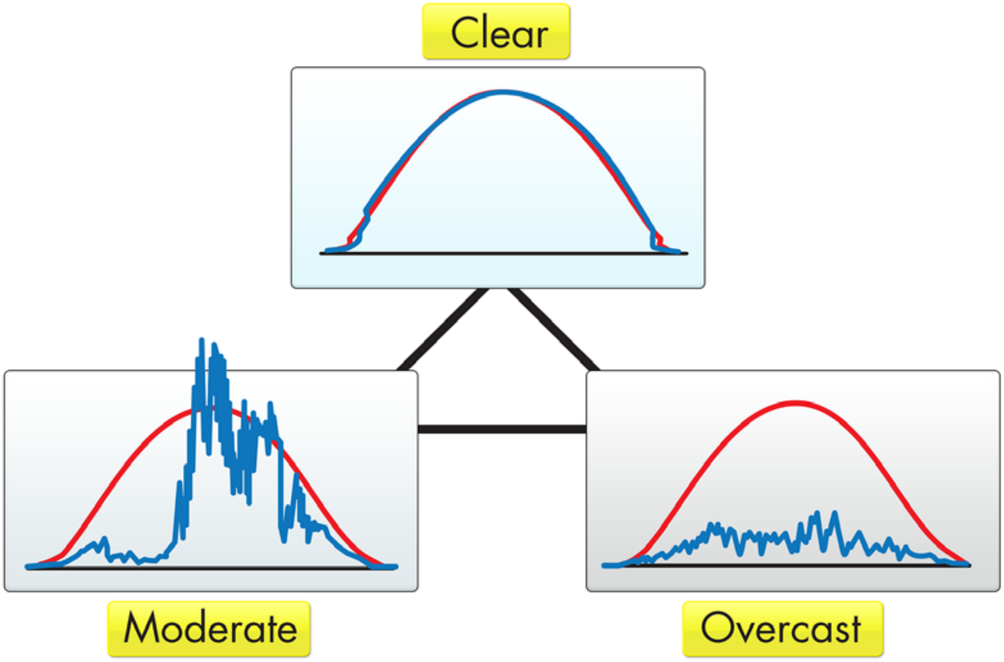



Figure 4: Forecast scenarios

There are several different scenarios regarding forecast. Depending on the method used and the weather, there might be different issues. In ideal conditions, a clear prediction will take place, but they are usually not perfect. For example, clouds and temperature changes might produce a moderate case, or even an overcast one (EPRI, 2014).

This can lead to problems in voltage regulation, and will normally produce low voltage levels in certain nodes when there is an overcast scenario and high voltage levels when there is an undercast one, even if control measures were properly taken considering a perfect information scenario.

Apart from forecasting, key factor in this project, another variable that affects to a large extent is the amount of PV penetration in the system for a particular day.

In this project penetration will mean the peak embedded generation divided by the peak expressed as a percentage:

$$\%Pen = \frac{Generation_{\ peak}[kW]}{Load_{\ peak}[kW]} * 100$$

It might be variable depending on the case, and the specific load and generation assumed. The previous definitions and introduction leads to the case study.

## 2.2 CASE STUDY DEFINITION

In this section the rural network and the DigSILENT elements used in the modeling phase are detailed. This case contains the information about the rural network and shows the original distribution. A figure of this system can be seen in Figure 5.

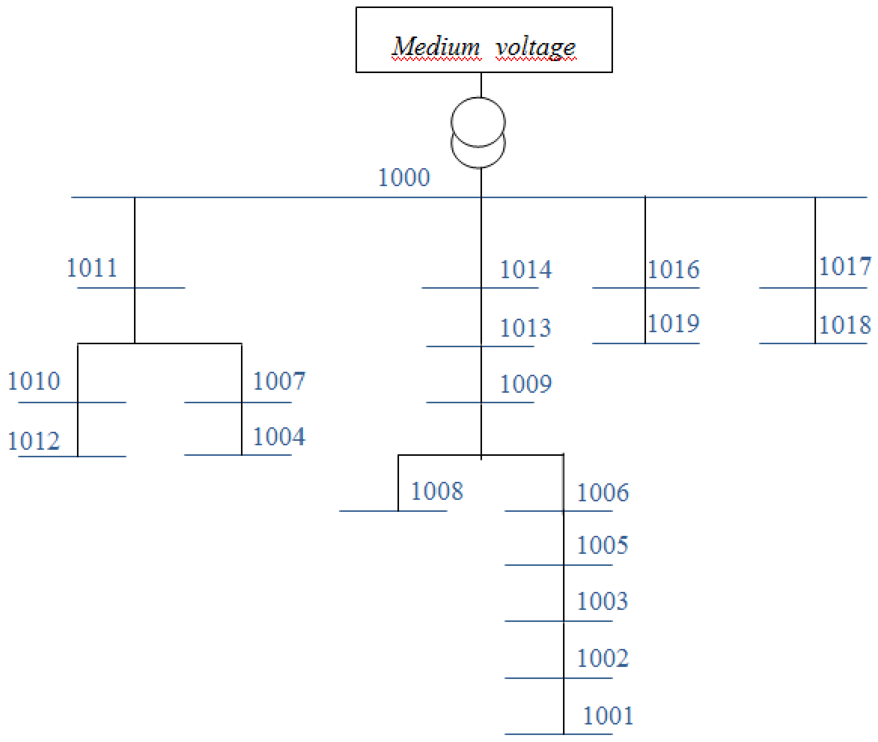



Figure 5: Rural network diagram overview

The network that will be analyzed is rural. There are quite big distances among consumption points and also considerable distances between the transformer and each node. This will affect several variables in a specific and different way that it would be in an urban framework.

This network is connected to an upper voltage level through a transformer of [0,4-15] kV that will eventually connect to the transmission network. Having the support of the network means a different context from an isolated system, which would have to control every variable as voltage and frequency by itself.

The correspondence between nodes and series nomenclature is shown in Table 5

In section 4.2 there will not be any PV unit generating. This is what has been called the original network, based only in data from the lines, on load tap changers (OLTC) for the regulator transformer (Two- winding transformer) and loads. The equivalent image using DigSILENT can be seen in Figure 50.

Inside DigSILENT a daily profile for the loads has been defined. A simplification has been considered: all the nodes have the same demand profile multiplied by a factor that is the peak consumption. The created average profile can be seen in Figure 6.

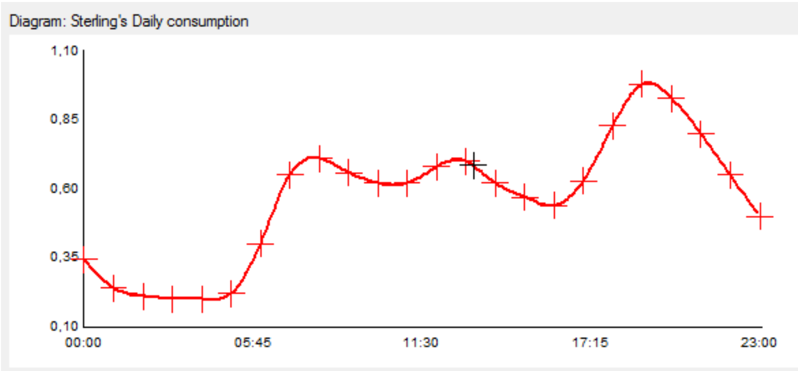



Figure 6: DigSILENT load profile

This model has been analyzed via Time Sweep Analysis, which are DigSILENT default scripts to calculate power flows and voltages for the requested daytime.

For a better understanding of the modeling in the following chapters, the elements that include the model are explained.

## *2.3 ELEMENTS OF THE MODEL*

In order to make the figures more understandable and to explain some choices that the author made a list of the main elements used in the modeling phase is detailed:

### 2.3.1 EXTERNAL GRID

The external grid represents the connection to the rest of the network. It can supply the demanded power for every case if the remaining elements have its variables inside bearable limits. It will be assumed that the voltage level at upper level remains constant at 15 kV.

### 2.3.2 BUSBAR

Although this is a low voltage network and there are no physical busbars as there would be in higher voltage levels, this was found as very useful for controlling purposes. It shows in a quick look the voltage levels of every node, and also in an output box the selected variables.

### 2.3.3 TWO-WINDING TRANSFORMER

The two-winding transformer is the main connection between the 15 kV and the 0,4 kV networks. For study purposes a possibility to change taps has been implemented. It will be analyzed if changing the taps at certain hours improves quality of service for the consumers.

Note that in real low voltage networks in the present time in Spain this is not common, although it could be implemented.

### 2.3.4 LINES

The key elements to transfer energy from one point to another. Every line has a defined resistance and inductance from original data, and a maximum power admitted that shouldn't be outstripped.

### 2.3.5 PV GENERATOR

They are probably the most relevant element in this project. It is the responsible for the over voltage problems that are originated by its energy generation.

As input variables the peak generation and the daily profile generation is given.

Normally, the power peak for every node will remain constant, and a profile simulating real conditions for every hour will fix the power generated. There will be three profiles in the study case:

-*Forecast profile 15 minutes in advance*: sent by a program, fifteen minutes before each point a prediction of generation is created by a program. It considers radiation expected by a software program, and can receive data from generation in order to improve the following forecasts.

-*Forecast profile at 00 am*: sent by the program, it considers only one invariant forecast for the complete day.

-*Real profile*: through measurement tools what actually happened is registered and accessible afterwards. These two profiles, that are processed data as input to the iterative method explained in play a very important role.

### 2.3.6 LOAD

For every internal node there will be a PV generator and a low voltage load, which simulates the consumption of that specific point. It has a defined peak load, as input data to the process, and it also shows a daytime profile. There might be different profiles depending on the case study. For example, it is not the same to analyze the consumption of normal houses in comparison to small industries.

### 2.3.7 PASSIVE VOLTAGE CONTROLLER

In sections 4.4.3, 4.3.3 and 4.5.3 this will be considered as a tool to generate reactive power that is consumed by the loads. Its use might mean significant loss reduction because apparent power is reduced, so current is reduced. A figure is shown in order to explain it visually.

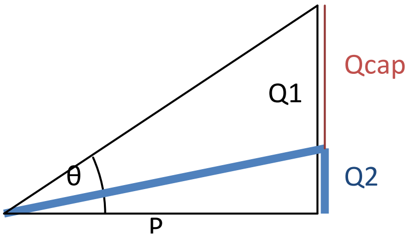


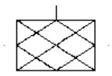

Figure 7: Power factor correction

Note that if too much reactive power was supplied by the capacitor, the reactive power could be over compensated and an increase of losses could happen. Also note that this is not the only variable to control losses through a line, regarding power flow analysis.

### 2.3.8 SUMMARY TABLE

A table has been added in order to specify the number of elements, the symbol used in DigSILENT and, among all possible variables, which ones have been modified in order to model the network.

Please note that not every element is used in every case. As it will be explained after, PV generators, tap changes and passive voltage controllers will gradually be added to test its behavior.

| Symbol | Name of the element | # of elements | Variables modified |
|---|---|---|---|
|  | External grid | 1 | V, $P_{max}$ |
|  | Busbar | 21 | V, # elements connected |
|  | Two winding On Load Tap Transformer | 1 | V, Tap position, Copper and iron losses |

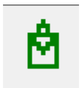
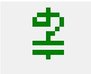
| | | | |
|---|---|---|---|
|  | Line | 19 | V, R, L, $S_{max}$ |
|  | PV generator | 19 | $P_{gen}$, Power factor |
|  | Load | 19 | P,Q, Load dependency |
|  | Passive voltage controller | 5 | $Q_{gen}$ |

Table 1: DigSILENT elements

# Chapter 3 TECHNICAL ANALYSIS

## *3.1 CASE STUDY*

In order to work with the model a structured iterative process has been defined and used. This process is divided into two parts: network modeling and study of the impact of forecasting.

The first part is network modeling. All the information available is added to DigSILENT for modelling purposes. A new project is created and inside the first study case all the graphical objects are introduced and modified to reproduce the initial line conditions. Then PV panels are introduced into the grid, and power flows are executed in order to check if desired conditions (voltage levels and total penetration level) have been achieved. This process concludes when the penetration conditions and overvoltage levels are in the intended levels, so Reference case is reached. This first step is summarized in Figure 8, and the result of its translation into DigSILENT language is shown in the annex, Figure 50.

The second part is the study of the impact of forecasting. Based on the info that the forecasting tool sends, certain time ahead several forecast generation profiles are created. This forecast profiles lead to estimated generation profiles. For each of them, there are different type of possible control actions (i.e. changing tap transformer). The best control action (e.g. the best tap) is selected for each type of control action.

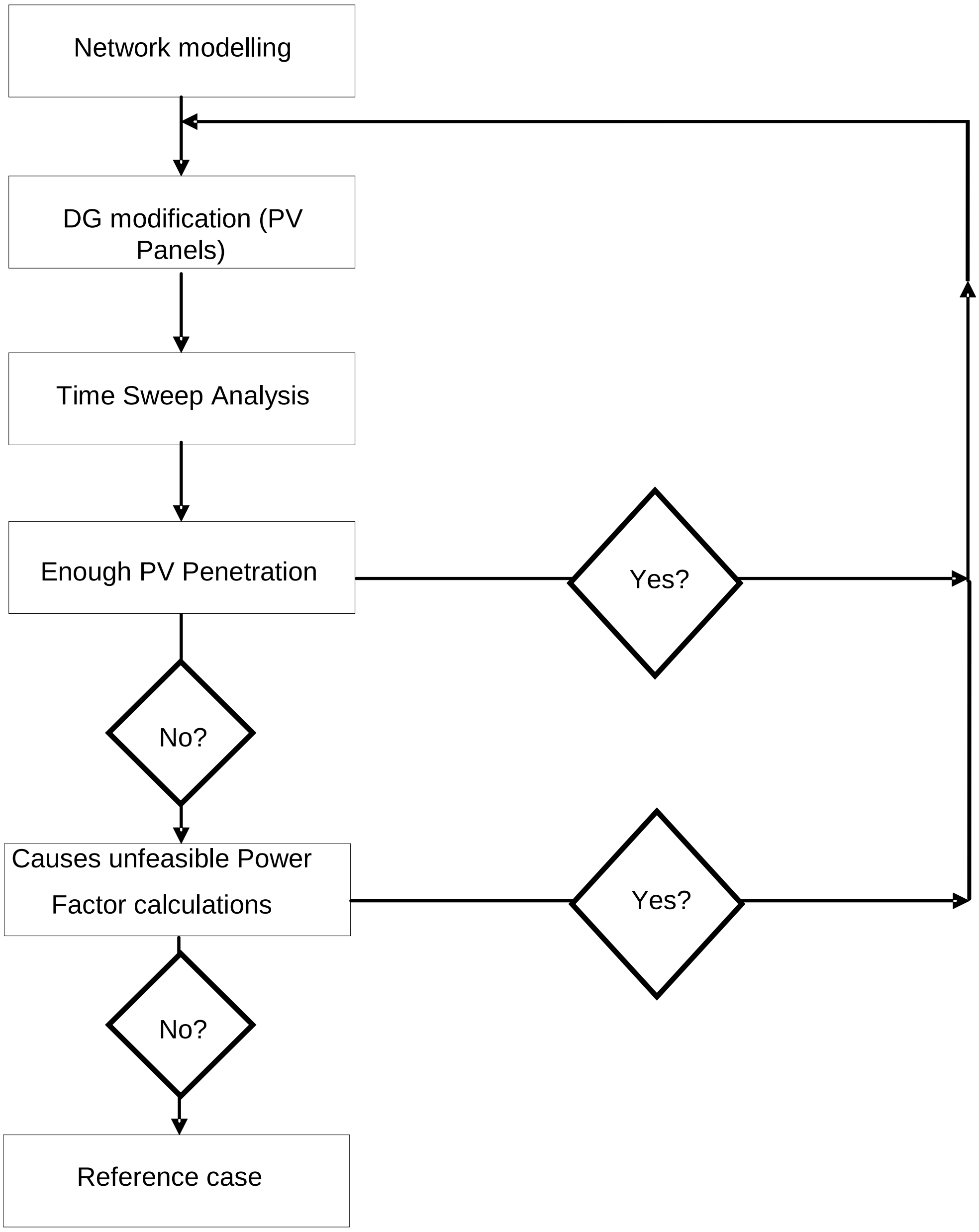



Figure 8: Iterative process until reference case

After following this iterative process to reach the reference case, another iterative process has taken place in order to analyze the impact of forecasting.

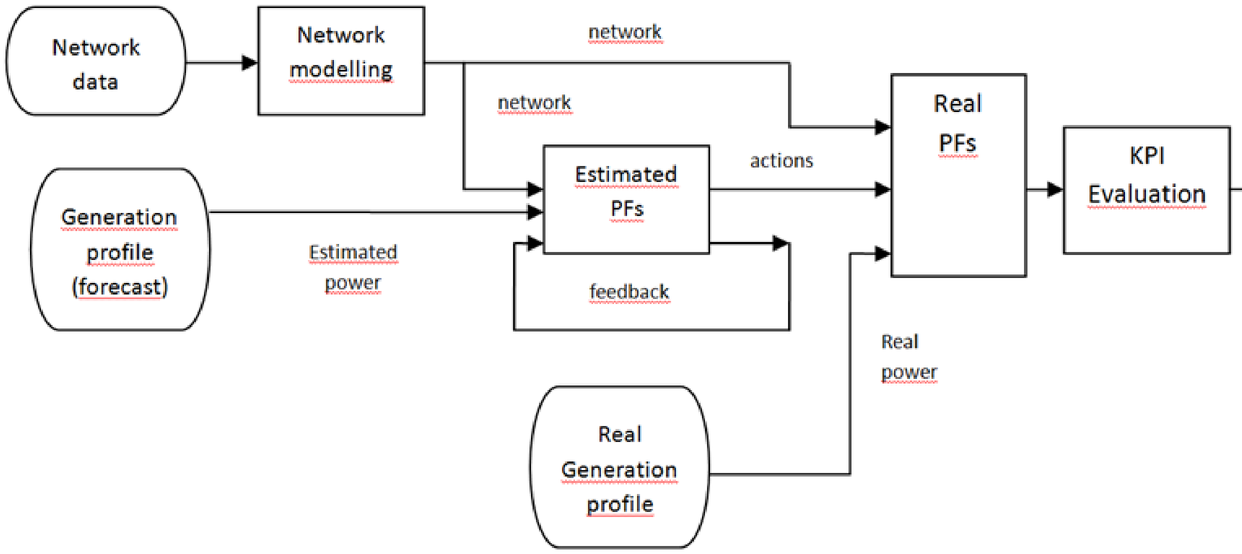



Figure 9: Real profile with action from forecast iterative process

The process in Figure 9 is explained: after the reference case was set, there is a defined PV generation forecast profile that will affect the voltage levels in every node. In the reference case set, it will lead to control actions that have to be defined depending on the forecast. The control possibilities ("Definition of actions") are:

- ❖ Changing on load the tap transformer.
- ❖ Introducing a capacitor to reduce losses.
- ❖ Alter the power factor of the inverter in each PV panel to make it absorb reactive power.

When those actions have been decided, an analysis of the network in case of a perfect forecast scenario can be done. Losses and voltage levels are monitored and it can be seen the impact that the defined actions have onto the grid. This grants that in case the real profile equals the forecast scenario (perfect information scenario) the problems related to high voltage levels are solved.

After this perfect forecast scenario is analyzed, another study case will take place, which is to analyze the impact of forecast on this network. It should be considered that a perfect information scenario is very rarely found in irradiance forecast, and the effects of the difference between perfect information scenario and wrong forecasts are analyzed.

In this project, three forecast cases will be inserted into the software, as it was introduced in Figure 4. Actual generation profiles come from real data obtained from PV generators on the rooftop of the IIT, UPComillas, scaled to simulate the effect on a rural network rather than just a building. A forecasting tool sends updated data every 15 minutes. With this information, several profiles were created:

- ❖ Forecast updating information 15 minutes before every hour.
- ❖ Forecast sent at 00am for the following day (not updated).

- Actual profile, obtained from real PV panels.

All this information was treated to show forecast against actual data. The three most representative cases in March 2014 are:

- Moderate. Corresponds to March 15th.
- Undercast. Corresponds to March 19th.
- Overcast. Corresponds to March 14th.

The power generation profiles can be seen below. In each figure the legend specifies what kind of profile it is.

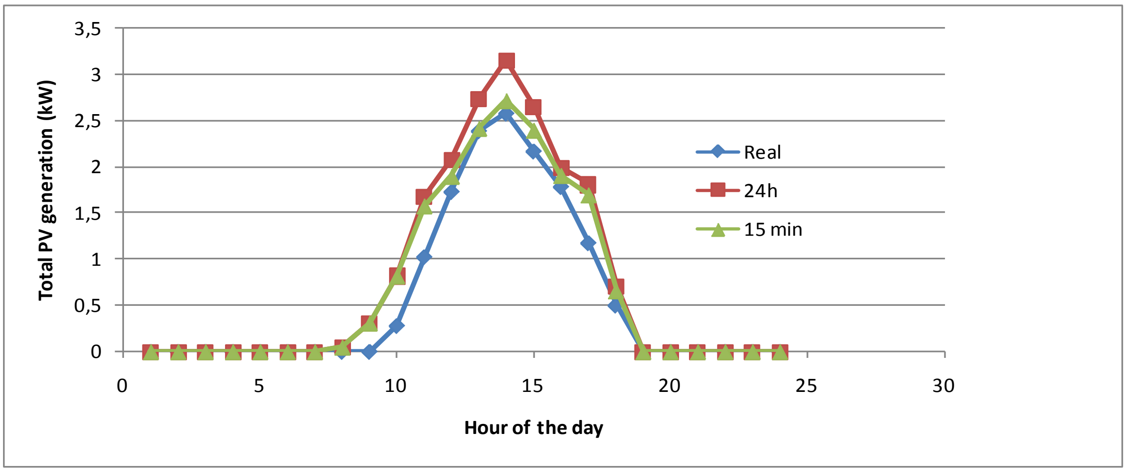



Figure 10: Moderate generation and forecasts.

The moderate scenario has been chosen to check that the problems created by generation in a good forecast can be solved with the control actions.

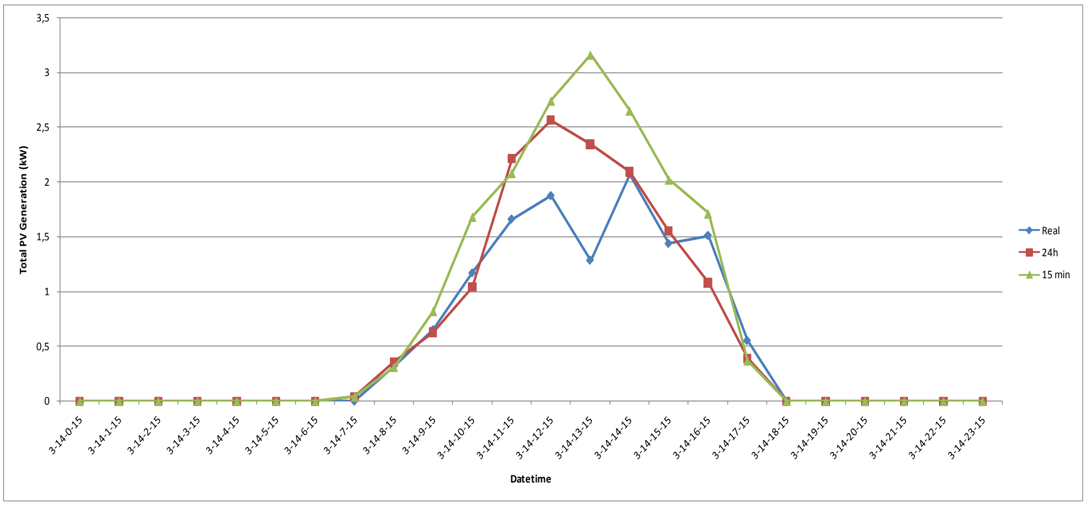



Figure 11: Overcast Real PV generation and forecasts.

This happens when the real case produces less power than expected. Note that there is a large error from the forecasts, and a bigger error from the forecast that is given after, 15 min in advance to the actual profile. This is an error from the real data received from the forecast tool that was not expected.

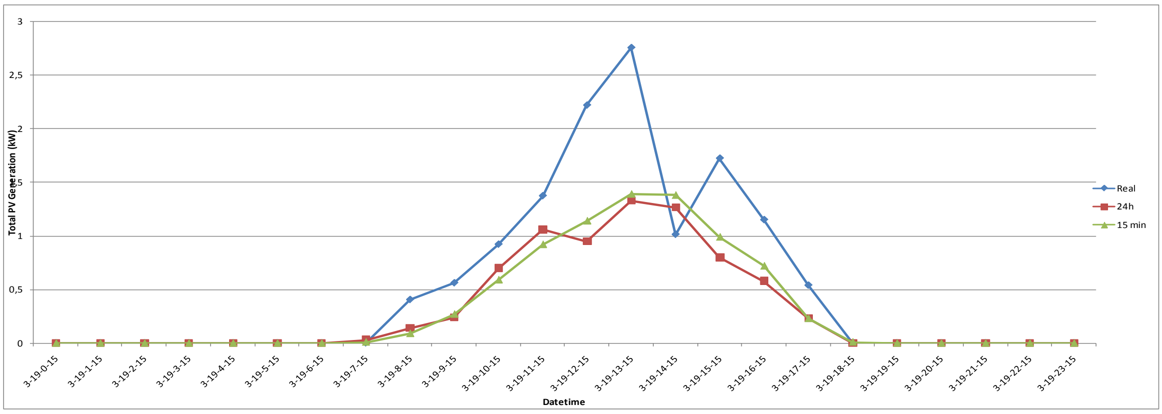



Figure 12: Undercast Real PV generation and forecasts.

Finally the undercast scenario when real generation is significantly more than forecast.

In this way, the impact on a clear, moderate and undercast scenario will appear and will be analyzed. In terms of forecast accuracy, it is not the same to have a clear or unclear scenario and forecast time window, as It differs how ahead is the forecast and the data updating frequency alters the result. In this case it is updated data 15 minutes before every hour (in the legend “15 min”) or not updated data for the whole day (in the legend “24h”), depending on the type of forecast.

The results of several analysis are shown in Chapter 4.

# Chapter 4 RESULTS

## *4.1 INTRODUCTION*

This Chapter includes all the results obtained from DigSILENT, which allow making an in-depth study of the rural network and its main variables.

At first, the basic modeling results and its study in case no generation is involved is shown. It includes losses and voltage levels for every node.

Secondly, a deeper analysis of the network studying control actions takes place. On one hand, it is checked if control actions solve the overvoltage problems that appear for every generation profile. On the other hand, the impact of forecast in the network for different scenarios takes place. Please note that for each forecast profile, an individual analysis to decide among several control possibilities has been done.

## 4.2 MODELLING RESULTS

This section describes the first results obtained from the modelling phase. The rural network described in Chapter 3 is analyzed for all the hours in a day. In the first stage no distributed generation will be included, so the following figures in 4.2 will not include any PV generation. Please note that the relation between series and nodes is listed in Table 6.

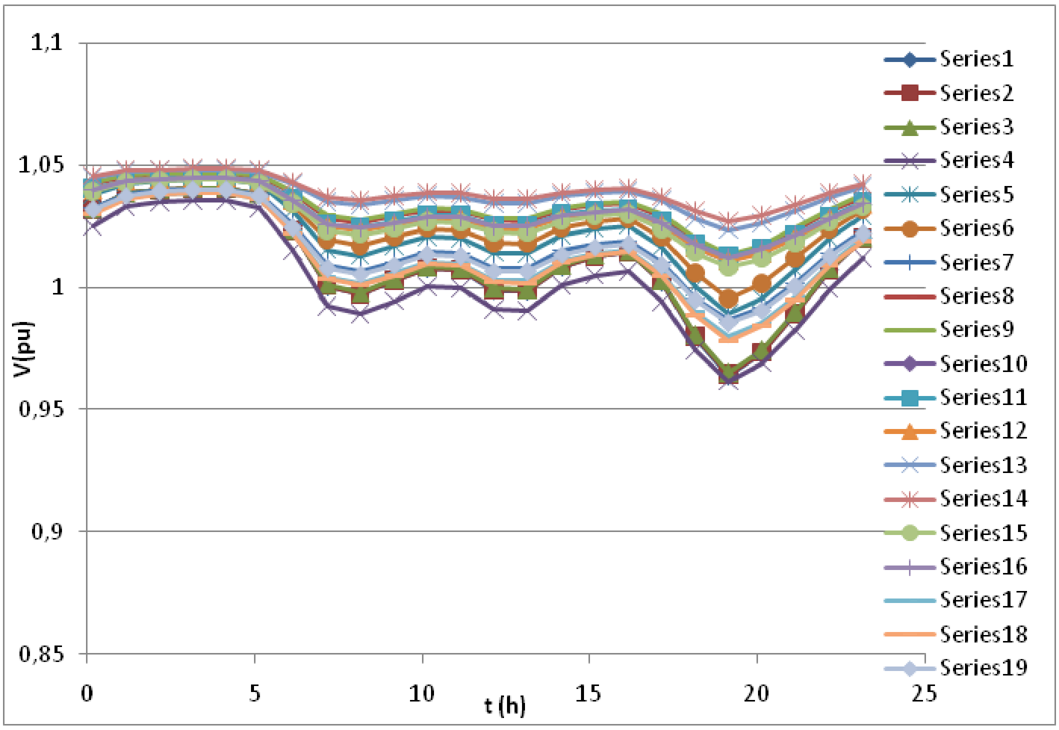



Figure 13: Voltage levels with no PV generation

In Figure 13, for every hour the voltage levels are shown in the original network. Note that no generation has been included yet, so it shows the voltage drops due to consumption and losses. It can be seen that voltage always remains inside the regulated limits, which are in Spain nominal voltage ±7%. In this project target voltage will be ±5%, so it includes some margin. It is also noticeable that the moment in which voltages are lower is approximately at 19 pm that corresponds to the average peak consumption, and shows the inverted shape of the total load and losses (Figure 14, Figure 15).

In Figure 14 losses are shown. There is a strong correlation between losses in the transformer and average demand.

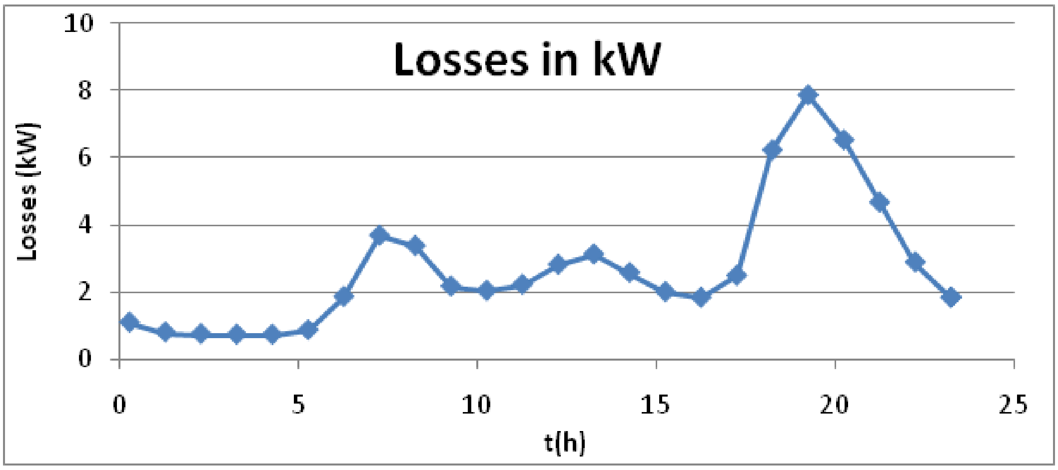



Figure 14: Transformer losses in no PV generation scenario

Then Figure 15 shows a representation of the total power balance calculated in the transformer busbar. It helps to understand the amount of power that is shown for every case. As it has already been said, generation is null at this first step.

The difference between generation and total load would be total losses for every point. Note that the Figure 14 only represents transformer losses. The remaining energy has been lost in low voltage lines and other elements with impedances that produce losses.

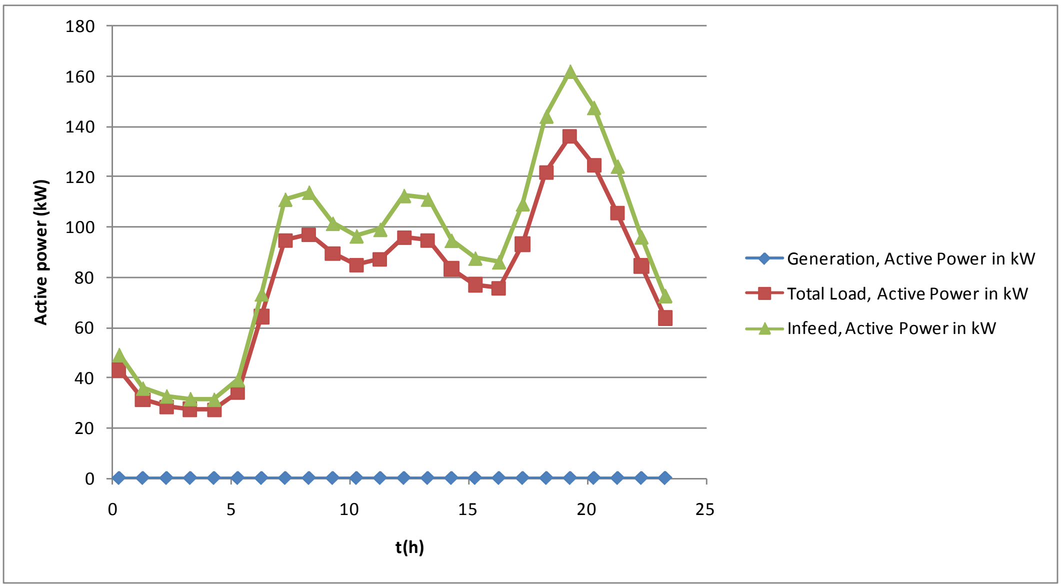



Figure 15: Generation, total load and infeed total power involved in no generation scenario.

The total amount of energy lost can be obtained from the power flow which shows the following table:

| *Time Sweep Analysis report from DigSILENT* | *0 generation case* |
|---|---|
| Total External Infeed | 2199,821 MWh |
| Total Generation | 0,000 MWh |
| Total Load | 2120,225 MWh |
| Total Losses | 79,596 MWh |

Table 2: Time Sweep table for no generation scenario

This table shows that total losses are 3.6% of the total energy supplied (generation+ total external infeed), when generation is null, is 3.6% of total external infeed.

Another analysis was done, to check that the theory in the previous chapters referring to the increasing and decreasing losses to different penetration levels is consistent for this case, regarding possible inverted power flows. It is intended to find the optimal PV generation for the classic generation profile and the rural network in the case study. The result from DigSILENT time sweep analysis is shown in the following table:

| % compared to case study generation | 0% | 25% | 50% | 75% | 76% | 77% | 80% | 100% |
|---|---|---|---|---|---|---|---|---|
| External infeed [MWh] | 2199,765 | 2064,078 | 1930,981 | 1800,287 | 1795,12 | 1789,96 | 1774,51 | 1672,42 |
| Generation [MWh] | 0 | 129,401 | 258,843 | 388,253 | 393,428 | 398,602 | 414,124 | 517,532 |
| Load [MWh] | 2120,169 | 2120,216 | 2120,212 | 2120,168 | 2120,17 | 2120,17 | 2120,17 | 2120,17 |
| Losses [MWh] | 79,596 | 73,263 | 69,612 | 68,372 | 68,382 | 68,396 | 68,461 | 69,785 |

Table 3: Optimal generation level for a specific PV panel distribution and network

In the table, “% compared to case study generation” means that 100% is the case study penetration shown across the whole chapter of Results. This is a complementary analysis that shows the penetration level that would make for that network configuration and load the optimal generation to minimize losses. Data from the table results in the following Figure:

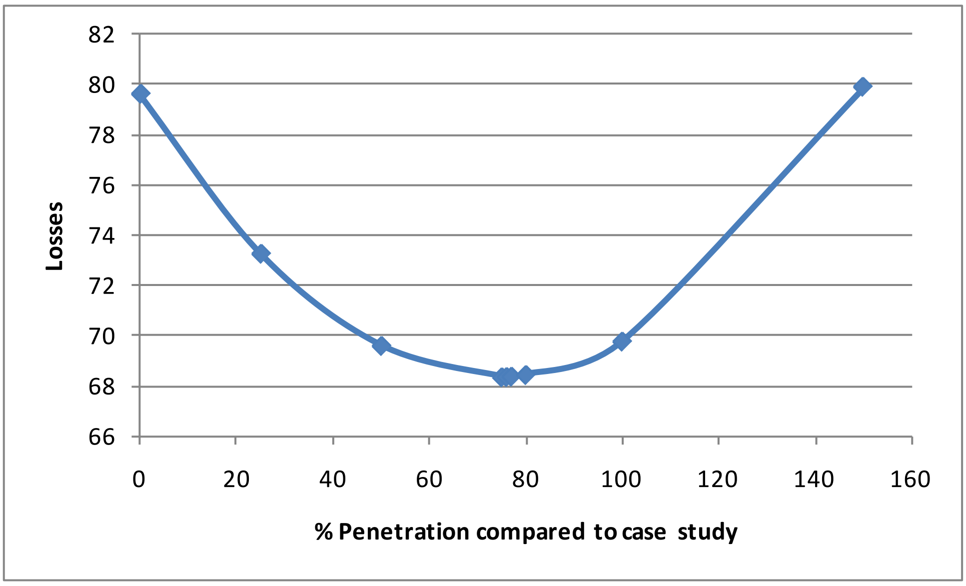



Figure 16: PV penetration- Losses in MWh

The results in the table show that a PV generation of approximately 77% of the case study generation would mean minimum losses if no control actions were applied. It shows parabolic shape, as expected. Losses are in MWh.

## *4.3 MODERATE*

This section refers to the results of the PV generation shown in Figure 10.

The shown profile is a moderate forecast, as explained in Figure 4. This means that the forecast error is considerable, but close to the real profile. The real generation profile is in this case the lowest one, followed by the forecast updated every hour 15 minutes before each point, and finally the largest error comes from the forecast which was made at 00h for the following 24h.

The scenario is usually found in sunny days and few clouds expected, that let the program which sends data do a calculation via solar radiation depending mainly on the variables associated to the sun for every day in the year. This is the closest circumstance to a perfect information scenario, so control actions are expected to be effective in this moderate scenario.

At first an analysis of the actual profile where there are no control measures is carried out. The associated problems and costs are analyzed. Afterwards, control measures are applied in different situations solving specific problems in each case.

## 4.3.1 ACTUAL PROFILE WITHOUT CONTROL

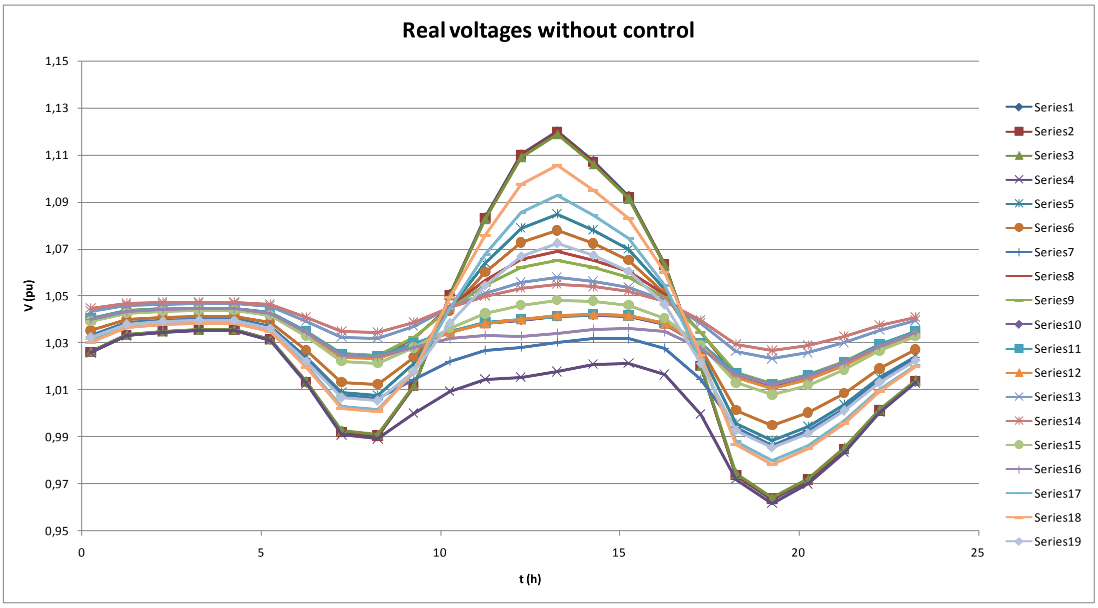



Figure 17: Actual voltage profile without control measures

As it can be seen in Figure 17 many nodes show its voltage over the limits. The maximum voltage peak is at 13h, 1.12 pu, at node 1001. Note that all overvoltages occur when PV generation is close to its maximum, and that this generation is spread out in the network.

All voltages over 1.05 pu have an associated cost due to breaches of the voltage limit requirements. In order to quantify this impact, every node with voltage over 1.05 has a cost per power unit assigned. Voltages are expected to be lower than 1.2 pu, that would be the voltage at which power is not supplied, with its negative value as it is a cost. (-1,8€/kWh). The remaining points are adjusted into a quadratic function until voltage 1.05 pu, associated to 0 cost. This curve can be seen in Figure 18.

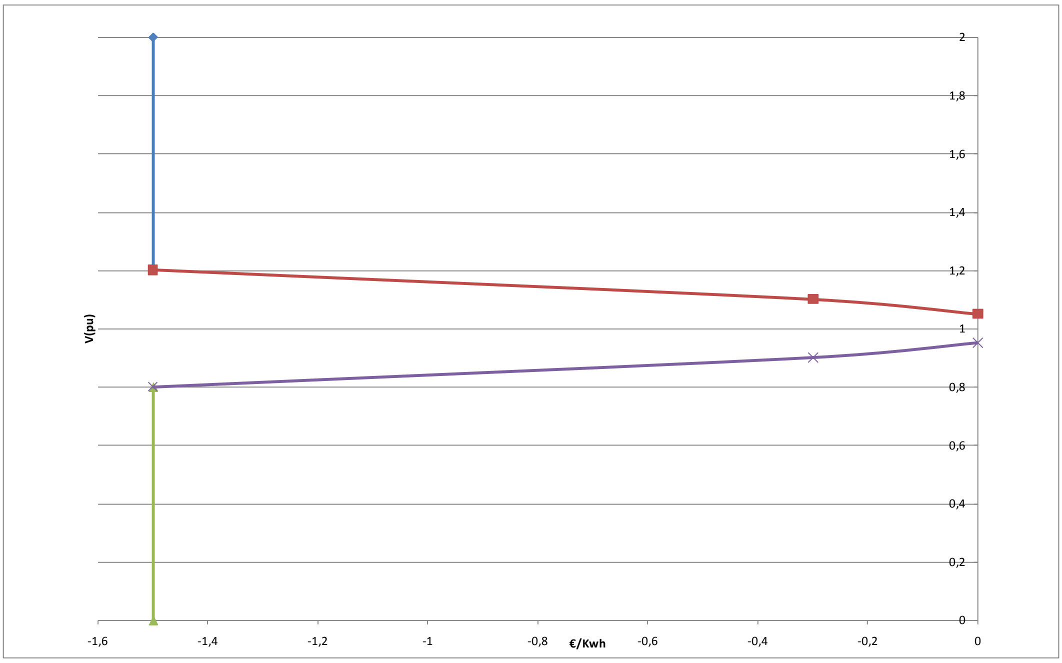



Figure 18: Overvoltage cost allocation

This graph relates the voltage at a node with its cost per kWh. To calculate the economic impact it becomes necessary to know the power that reaches each node, and the time interval in which that power is introduced. In this particular study, as most nodes behave on a similar way, an approximation of taking the average power for every node has been assumed in order to facilitate calculations. Also note that the time resolution is one point per hour.

To calculate the economic impact of voltages, for each point the cost according to Figure 18 is obtained. Then the product of each voltage times the affected power at a time period (1h) is calculated, and finally the addition of all points at all times with each particular power is obtained. An example of the calculation process for a single point is shown:

$$V = 1{,}083433\ in\ node\ 1001\ at\ 11am \rightarrow 0{,}25c€\ /\text{kWh (Figure 17)}$$

$$P = 5{,}19kW\ on\ average\ for\ that\ node\ at\ that\ time$$

So the cost for that node with that power at that time is:

$$\varsigma = \frac{0{,}25c€}{kWh} * 5{,}19kW * 1h = 1{,}30c€$$

For this “Actual profile without control measures”, after calculating the addition of the cost generated by all nodes, the result was -51,36€ for that operating day. It is a relevant amount that leads to think that possible solutions for that PV penetration levels could achieve interesting savings.

In order to understand better the case study, some Figures regarding power and voltage in case no control is applied are exposed.

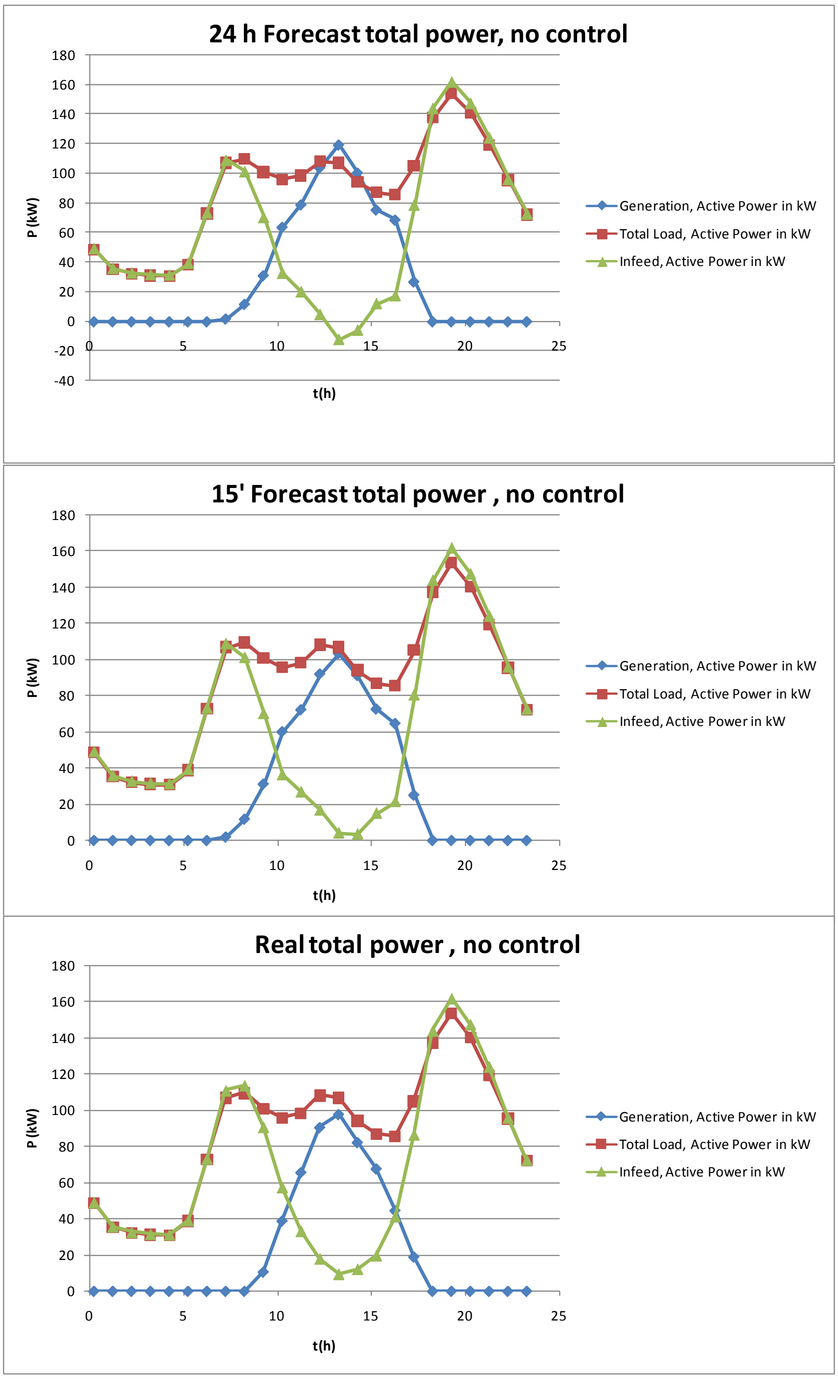



Figure 19: Moderate Real total power, without control

In Figure 19, infeed is almost null at the peak generation moment for the updated forecast and the real curve, but regarding the forecast made at 00am (24h forecast) it can be seen that generation exceeds demand, and after substracting losses there is a small negative infeed, so energy is being exported from rural to medium voltage. The network is supposed to accept it. If it was not possible, there could be an instrument as a last resource to stop generation (known as curtailment).

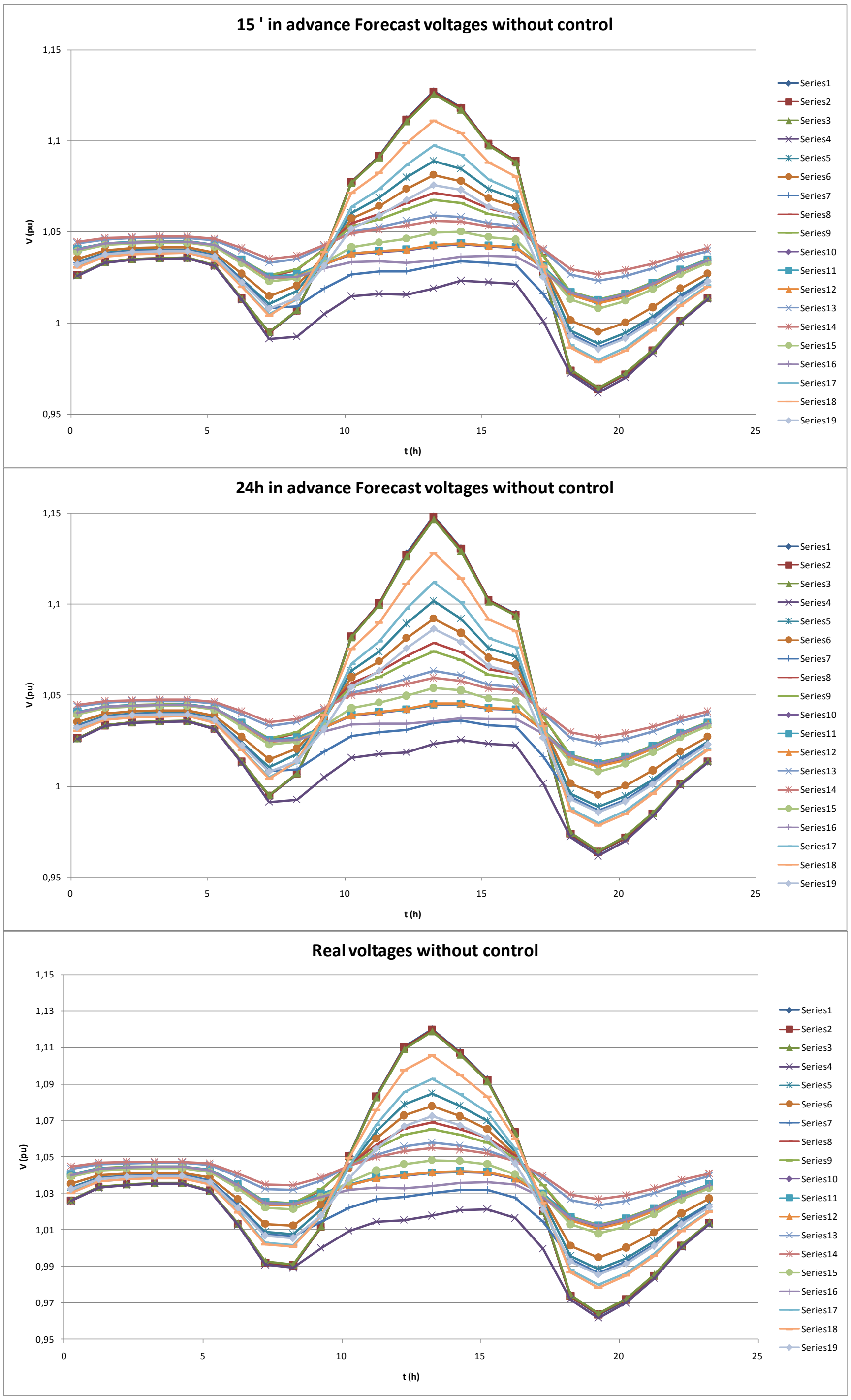



Figure 20: Moderate voltage profiles, without any control

Figure 20 shows the voltages for every node across the day. There is a strong correlation between the peak generation and peak voltage, as expected. Note that the peak generation does not lead to a linear voltage growth.

The voltage problems due to the high penetration are now clear, and some possible solutions or optimizations are shown in the following sections. The first voltage control action will to change the tap of the On Load Tap Transformer, and the second one will be the power factor control in each PV unit.

Some capacitors could also be placed, reducing losses due to power factor compensation.

### 4.3.2 TRANSFORMER TAP CONTROL

This is the first voltage control measure. In order to simulate this, in DigSILENT all conditions were specified, and there were two different executions. The first one with no control measures, at the hours in which it was not necessary. The second one applies to the specific hours (10h-16h), when the tap was changed.

In Figure 21 it can be appreciated the sudden voltage drop when the tap transformer is set to "-1", that is the immediately lower possible position. Other possible positions would be natural positions from +2 to -2, including 0. Please note that every tap change means 5% of voltage variation at the transformer busbar. The tap change decided after the analysis of the forecast, which indicated the tap change at 10am, to avoid high voltages during peak generation.

Note that control actions were decided when the forecast was given, before the actual profile appeared.

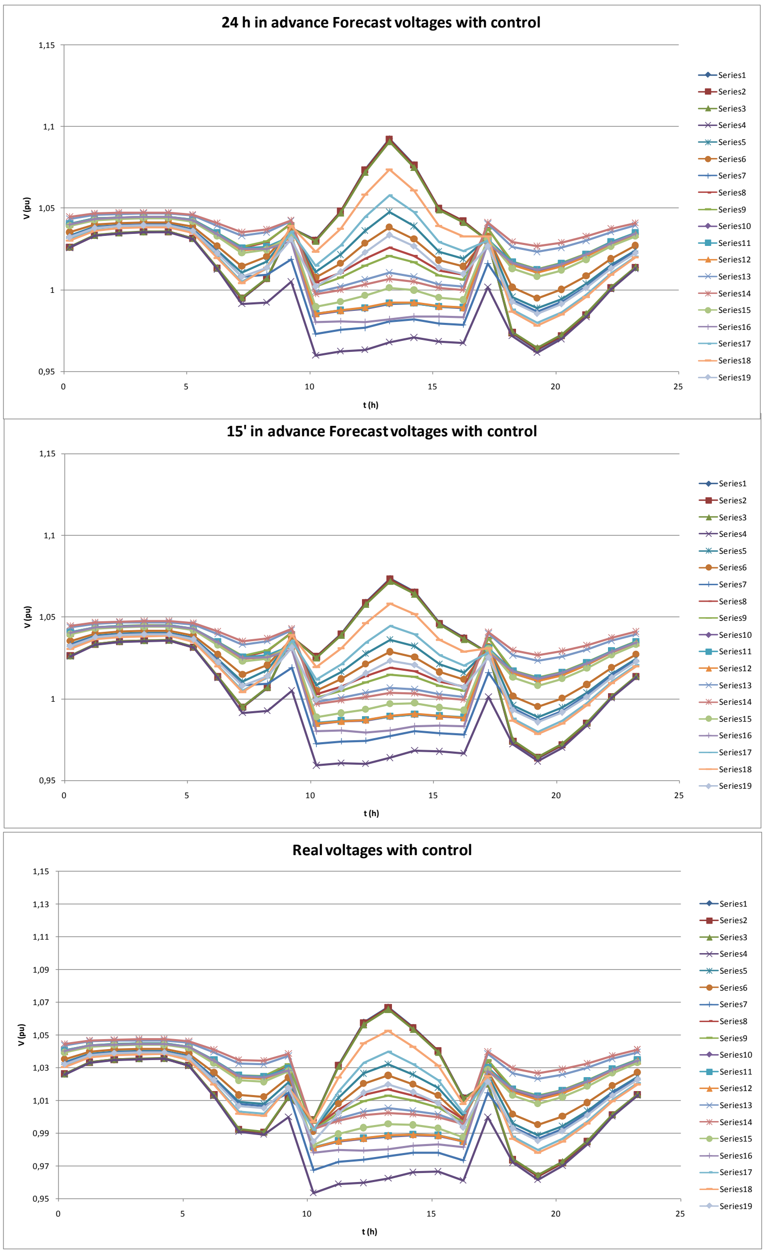



Figure 21: Moderate voltage profiles, with transformer control

This figure shows the effect of changing the tap of the transformer. The two upper figures plot the simulation of the forecast profiles on the network. This leads to the decision of changing the tap of the transformer at 10am to a lower position and rise it back at 4pm. This is shown in both figures, just before the most critical nodes (1001,1002,1003,1017,1018,1019 in Figure 5) reach the 1,05pu voltage target level.

With this control measure voltages at critical hours are reduced, but it is not enough. There are voltages still clearly outside the limits, so more control actions should be determined in order to solve them. The following Figure 22 shows for the real profile the voltage profile in a different way. Every line represents an hour of the day, and each line shows the voltage at the busbar.

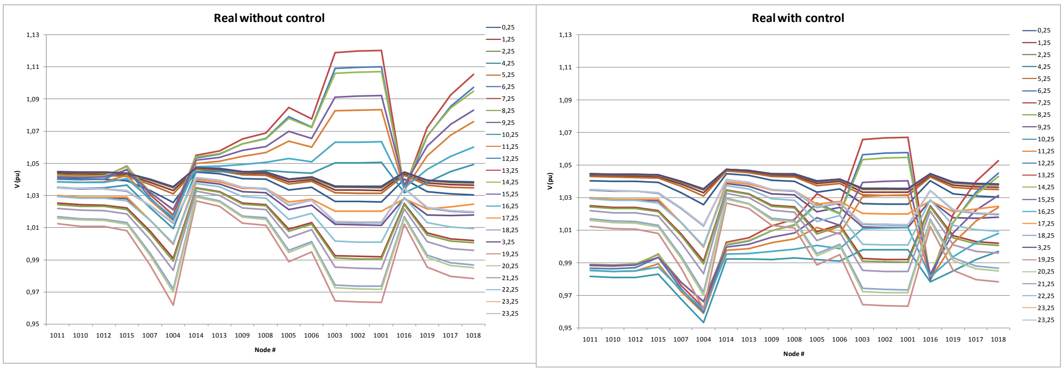



Figure 22: Moderate Real generation profile, comparing with and without transformer control

Figure 21 shows for every node the voltage levels at each hour. In this case there are three hours that produce in the three furthest nodes (1001,1002 and 1003) a maximum overvoltage of 1,067 per unit after the tap transformer is set to a lower position. Please note that for design purposes the target level is nominal voltage ±5%, so it is not yet a successful solution. This will be completed in the following sections.

From another point of view, transformer losses through the day are shown.

The left part of the figure is when the tap transformer is set to the neutral position, and the right side is when it is set to the lower position. Note that in case it affects, it should only be significant for the control time (from 10am to 4pm).

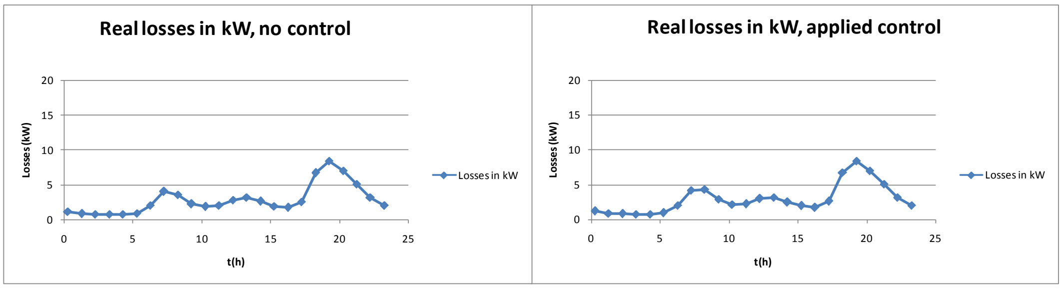



Figure 23: Moderate Losses in real transformer control scenario

In this case, the variation of losses is negligible, there is a very reduced impact.

### 4.3.3 CAPACITORS AND TRANSFORMER TAP CONTROL

This is the second aforementioned technique. It is introduced, as it was explained in 3.1.7, to reduce the power factor and therefore reduce losses, so it is closer to a network optimization technique and, in this case, it is not a voltage control technique. Voltage would only arise introducing reactive power to the power flow.

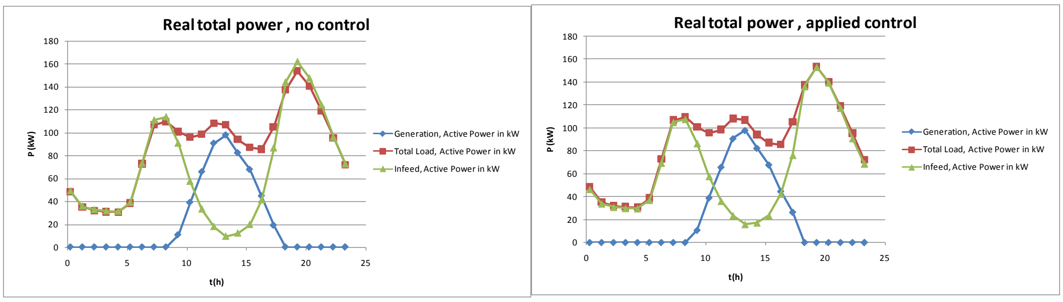



Figure 24: Moderate Real total power, comparing with and without transformer & capacitor control

The following figure shows in the left side the real generation profile when no control techniques are applied, while in the right side it is plot the same real generation profile when the tap of the transformer is set to the lower position, and at the same time (from 10 am to 4pm) the capacitors are switched on.

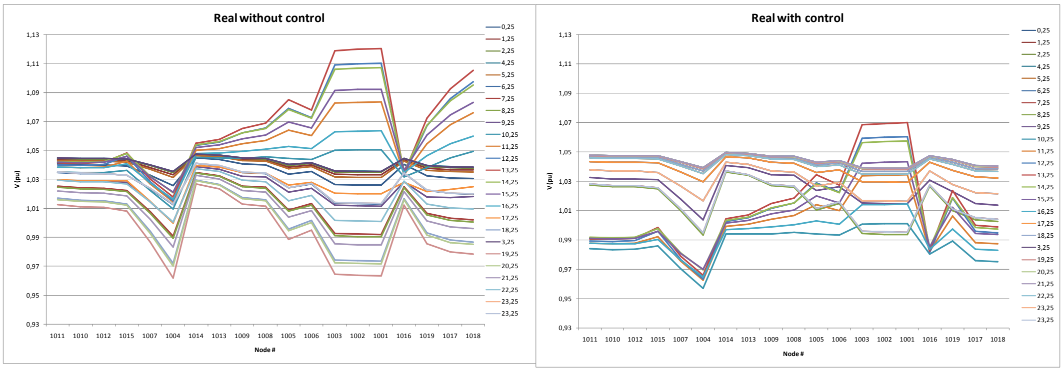



Figure 25: Moderate Real generation profile, comparing with and without transformer & capacitor control

As expected, voltages slightly rise (+0.5% for the most critical busbar, at 13h) in Figure 25 compared to the previous case, due to the effect of reactive power growth in the power flow.

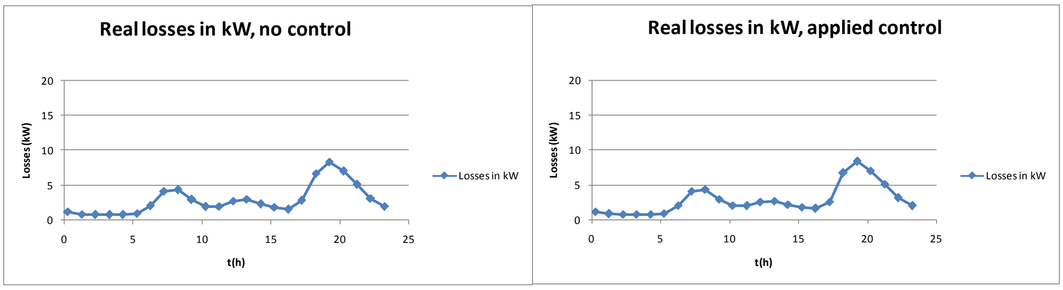



Figure 26: Moderate Losses in real transformer and capacitors control scenario

It might not be appreciated with this figure, but DigSILENT points out a decrease in the losses in the calculations of 0.7MWh, that corresponds to a 1% of total losses.

### 4.3.4 POWER FACTOR CONTROL IN INVERTERS AND TRANSFORMER TAP CONTROL

This section is an expansion to the previous ones. In order to reduce voltage levels that are not reduced as needed in the previous sections, another control technique is applied.

It was seen in the previous section that capacitors did not lower the voltage, so in order to achieve target voltages the inverters of the PV units will be connected to absorb reactive power at a power factor of 0.8 and at the same time the transformer tap is set to the lower position (from 10am to 4pm). This will lower the voltages, as can be seen in Figure 27 and Figure 28.

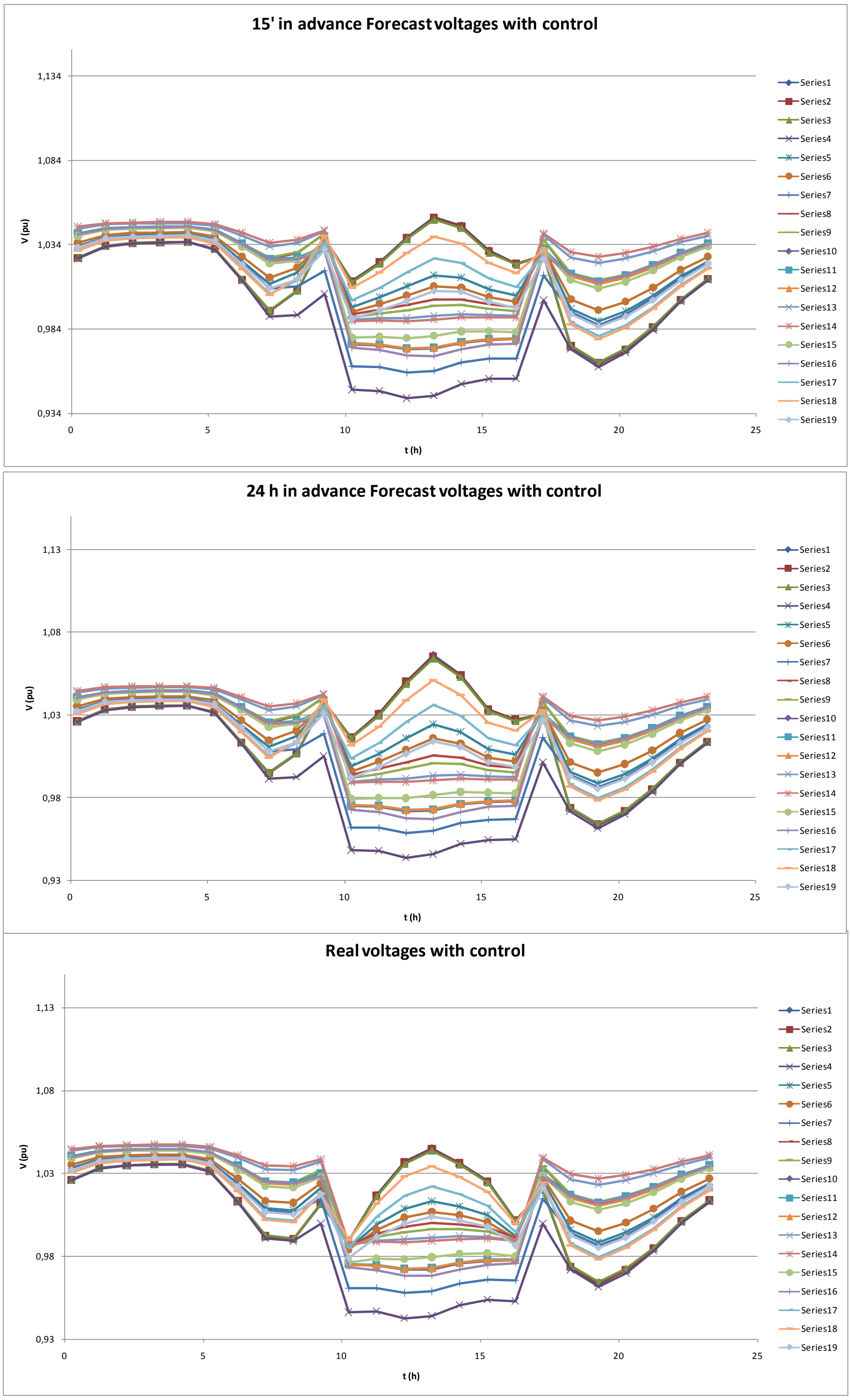



Figure 27: Moderate voltage profiles, with transformer & inverter control

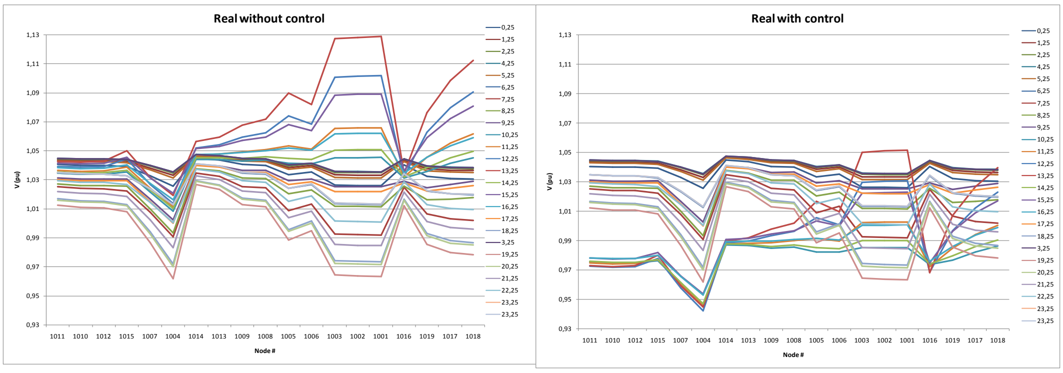



Figure 28: Moderate Real generation profile, comparing with and without transformer & inverter control

If the inverters consume reactive power with a power factor of 0.8, there is a double effect. The active power generated is decreased, and at the same time the voltage is decreased because losses are higher (current increases so the voltage drop through the lines increases).

This leads to an increase of losses at critical control hours, which becomes clear looking at Figure 29, where there is a peak of losses at midday hours.

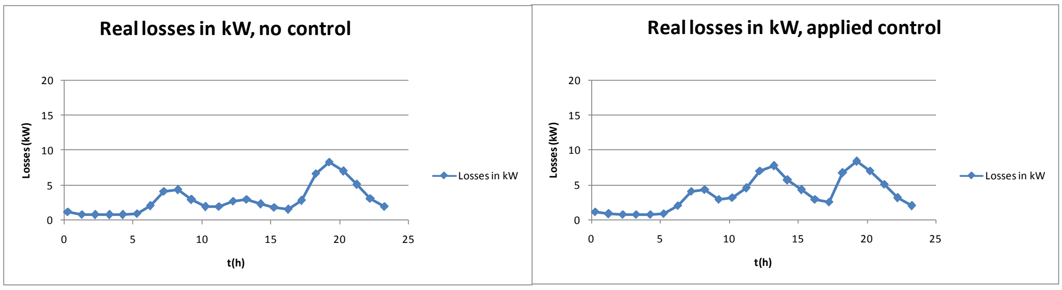



Figure 29: Moderate Losses in real transformer & inverters control scenario

For this moderate forecast situation, it can be seen that control techniques solve the voltage problems.

## *4.4 OVERCAST*

This section applies to the model the forecast and actual profile previously shown in Figure 11. Regarding both forecasts (24 hours in advance and 15 min in advance), and deciding the best moments to apply control, the same methods will be employed, except for the capacitors control case in the 15 minutes in advance case, that will lead to a two step change for critical hours. Note that this is an overcast scenario for both forecasts, and that control methods were decided before knowing the real generation curve.

There is a large forecast error, which occurs more frequently than desirable in real conditions. In fact, in this case the forecast with updated data is much worse than the forecast done for the whole day at 00 am the same day. This shows a real data case, and the forecasting tool might not send accurate data due to different reasons. Note that this is a rare case, moderate profiles are much more frequent, but this study tries to cover extreme cases for that particular month.

### 4.4.1 ACTUAL PROFILE WITHOUT CONTROL

Analyzing the economic cost of overvoltage levels if no control measures are applied with an analog procedure to the one in 4.3.1 results in -29,48 € for that operating day, which is clearly lower than the first situation analyzed. This can be explained by reduced power generated by PV units which results in overvoltages for that particular cloudy day.

For a better understanding, some Figures regarding power and voltage are exposed in case no control actions are applied.

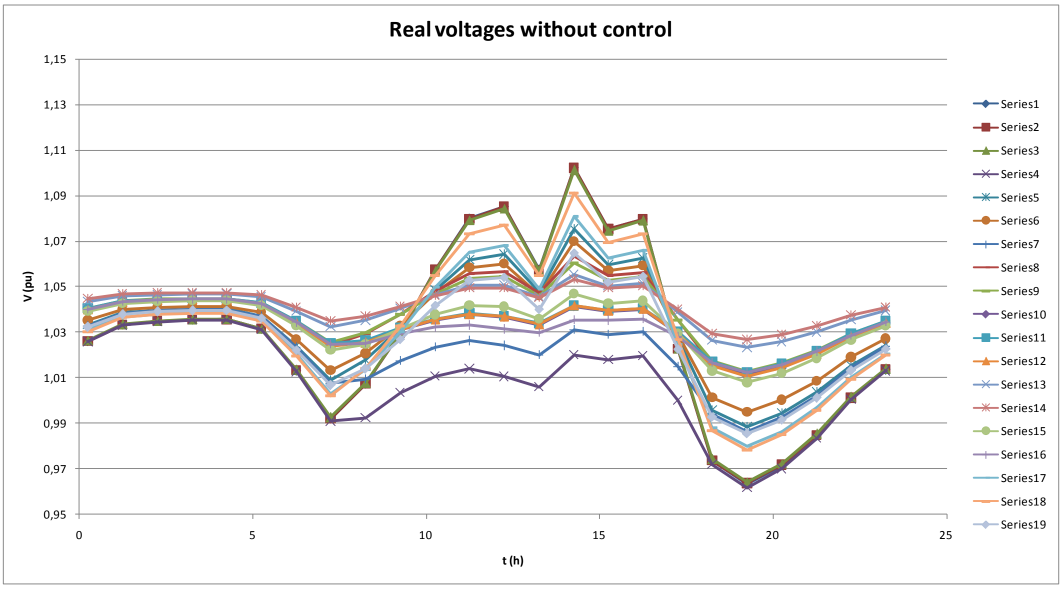



Figure 30: Overcast actual voltages without control

Due to the climate for that cloudy day, the voltages during the midday hours are very variable, because of the high dependency on PV for this case study. Note that voltage levels are not as high as they were in the previous analysis.

In Figure 31 voltage profiles for the case where no control is applied can be seen.

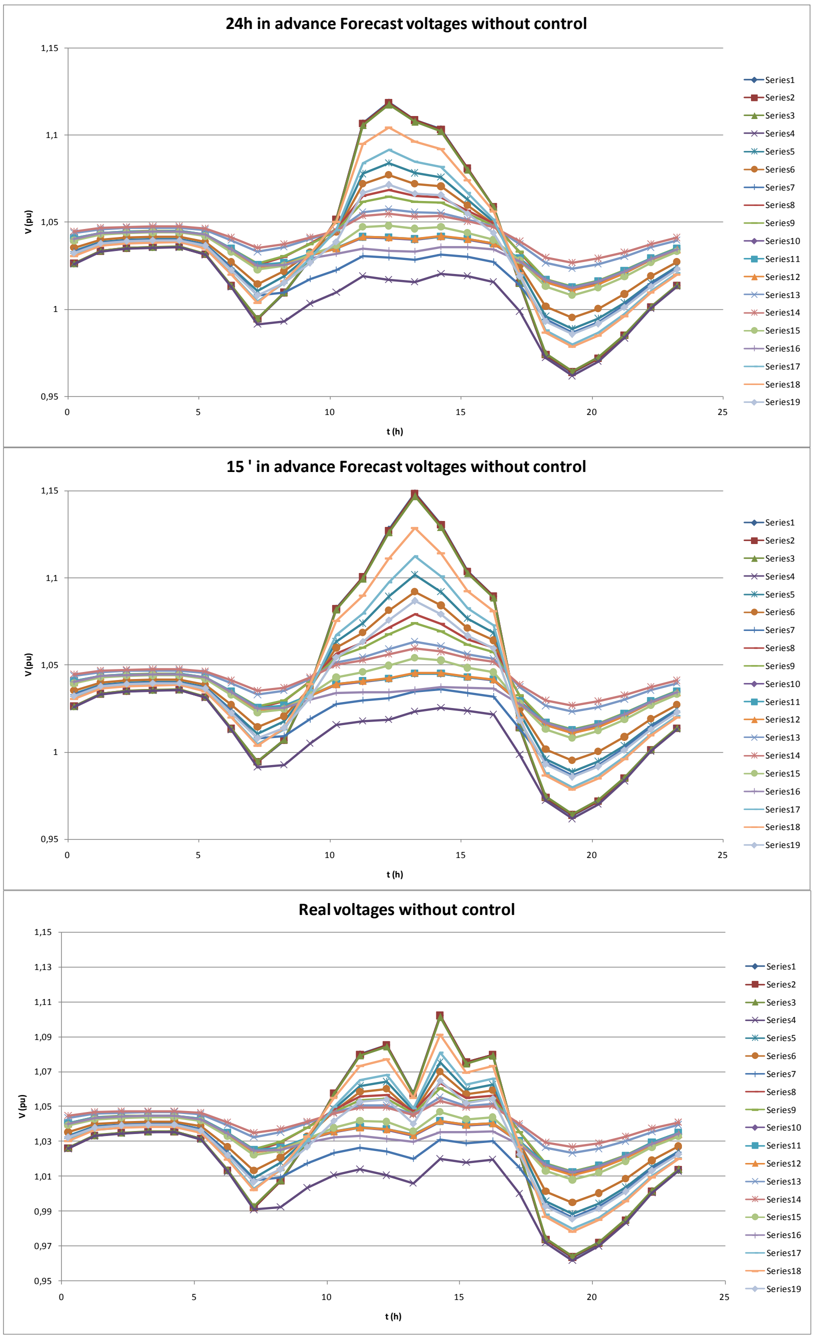



Figure 31: Overcast generation, total load and infeed total power involved in no generation scenario.

As it can be seen in the previous figure, higher and lower voltages are related to the expected profiles, but the actual profile shows a clear descent. More precisely 1,149 pu volt for the forecast with data updated every 15 minutes against 1,05 pu volt that shows the actual case, 9,9% of error in voltage levels related to a 58% of power forecast error.

## 4.4.2 TRANSFORMER TAP CONTROL

Only considering the transformer as control variable, and regarding the figures which show a high overvoltage, all of them will be applied a step down (except capacitor case in the highest generation forecast). This is the best solution for both two forecast cases, because even for the highest voltage (15 minutes in advance forecast) the second step down would mean undervoltage levels (lower than 0.95pu) for seven nodes, instead of two overvoltage nodes that shows if one step down is applied.

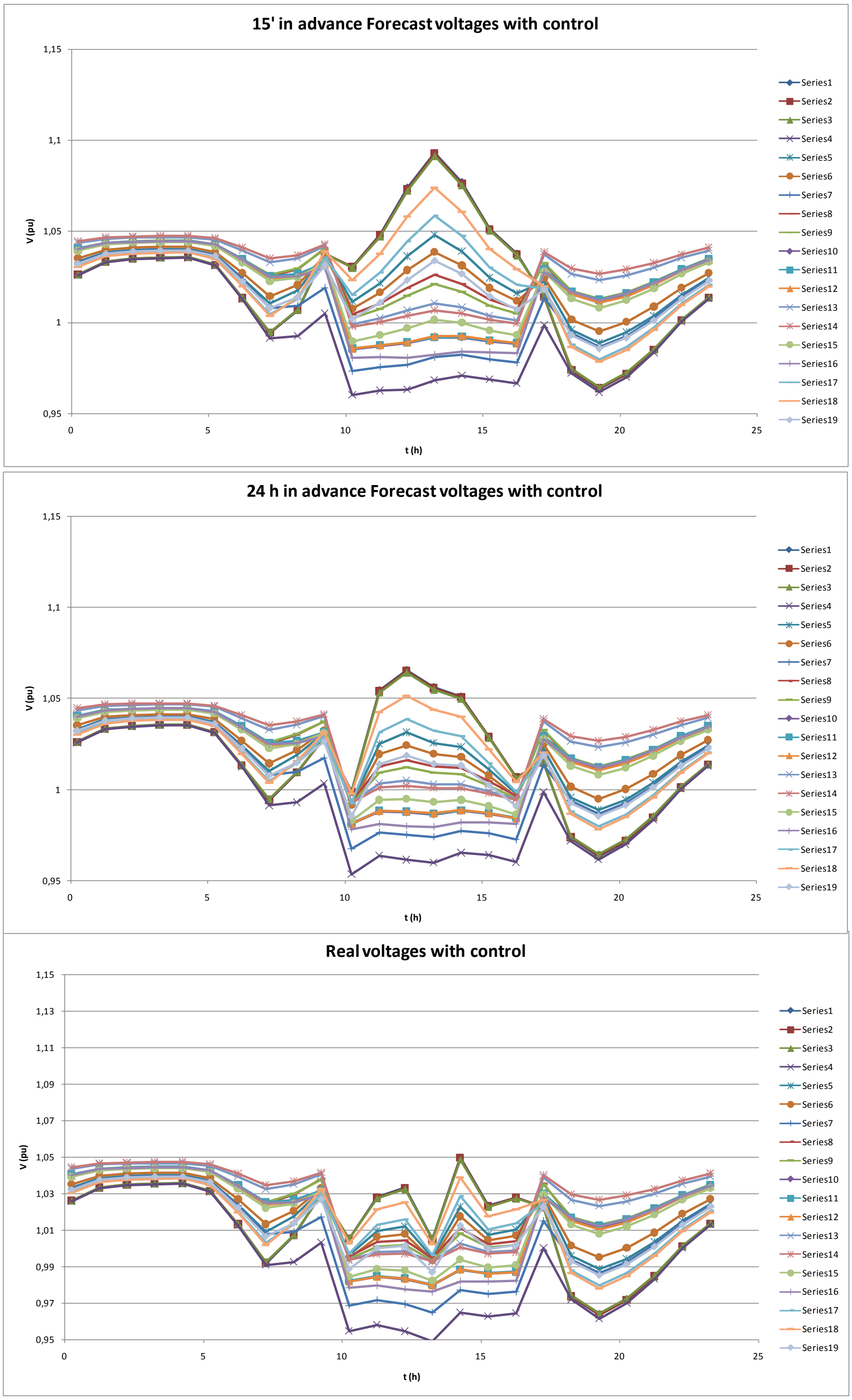



Figure 32: Overcast voltage profiles, tap transformer changed

Please note that the voltage reduction applied by the transformer is not exactly a 5% as it might be expected or is sometimes simplified to. There are multiple nodes at different distances that make different voltage drops and even with different loading at every time that make inconstant transformation ratio. The comparison between the ratio to prove this is shown in Figure 33.

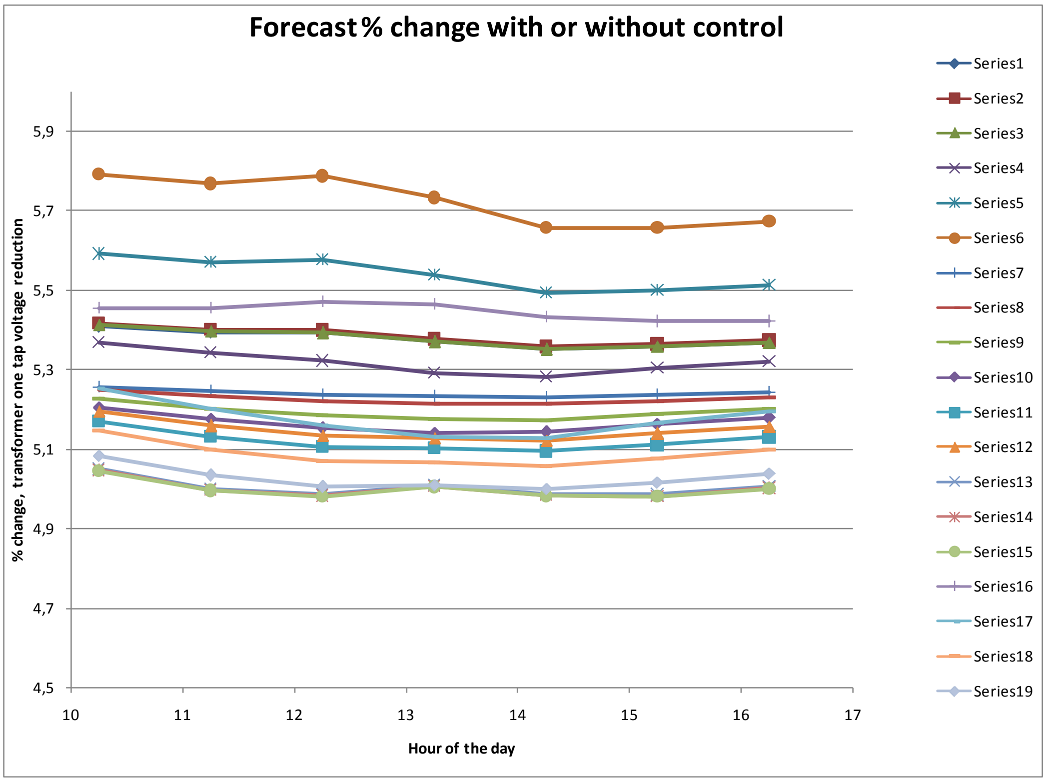



Figure 33: Overcast Percentage of voltage change comparing with and without transformer tap change

The results in Figure 34 show the effect of lowering the transformer tap. The points show the ratio between the voltage before and after the transformer tap was changed. It demonstrates that the transformation ratio in the primary and secondary winding does not correspond exactly to the change in the number of turns, but differs owing to the power flow.

From another perspective, with this scenario the real voltage cone would be perfectly inside the limits, with less control actions that were determined by both forecast profiles. This is due to overcasting.

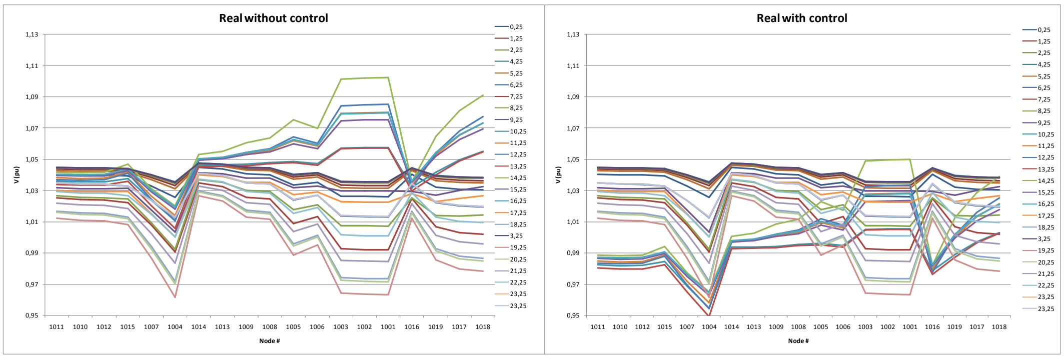



Figure 34: Overcast Real generation profile, comparing with and without transformer control

In the control period (10h-16h) it is shown a clear reduction of losses. It means more than 1MWh, almost 2% of total daily losses. Note that there is almost no voltage dependency on loads on this model. This change is due to the tap change and its associated power flow modification.

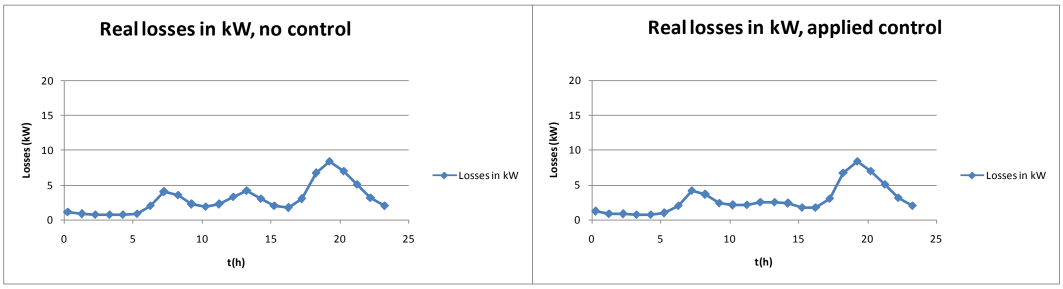



Figure 35: Overcast Losses in real transformer control scenario

## 4.4.3 CAPACITORS AND TRANSFORMER TAP CONTROL

If the capacitors are added as a control measure, the expected results are an increase of voltage and a reduction of losses due to power factor compensation. In this case, including five capacitors of 2,5 kVar each, distributed in the furthest nodes, means an increase of less than 1% in voltage, so the voltage is very similar to Figure 22. It is not recommended to include too much reactive power because there is a risk of over-correcting the power factor. In this case this is less than 10% of the peak demand, and less than half of the most reduced demand, to avoid further problems.

The only different case is the problematic forecast, which requires two tap changes. For simplicity and as they comply with the requirements, both are diminished and enlarged at the same time (10am up, 4pm down).

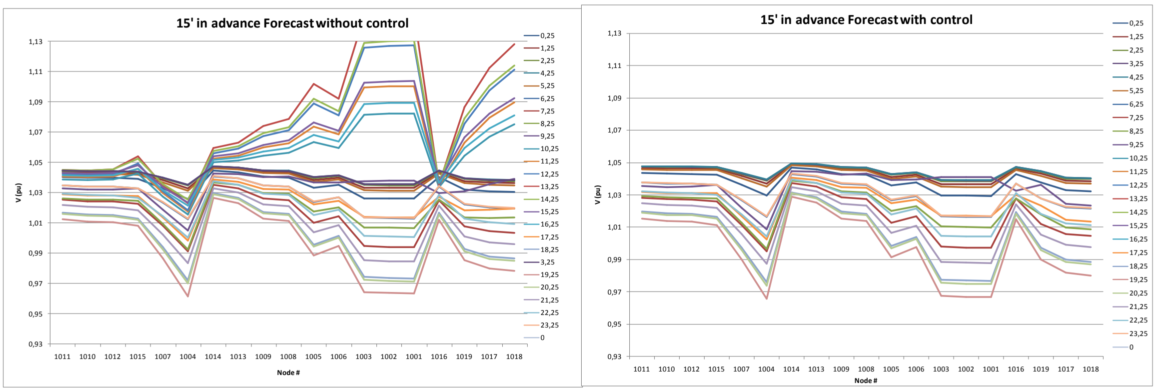



Figure 36: Overcast Real generation profile, comparing with and without transformer & capacitor control

The double tap change means that for the 15 min. ahead forecast, the problems would be solved, and there would not be any voltage outside its limit.

The problem is when the real generation comes, which is not in accordance with the forecast. In that case, for the actual generation it would mean three nodes with voltages under its limit (1001, 1002 and 1003). The associated cost of undervoltages is in this case 12,04€.

Regarding losses, this results are shown, obtained from two different sources:

On one hand, total infeed in Figure 37(external support) is slightly decreased. Load is almost not affected by voltage.

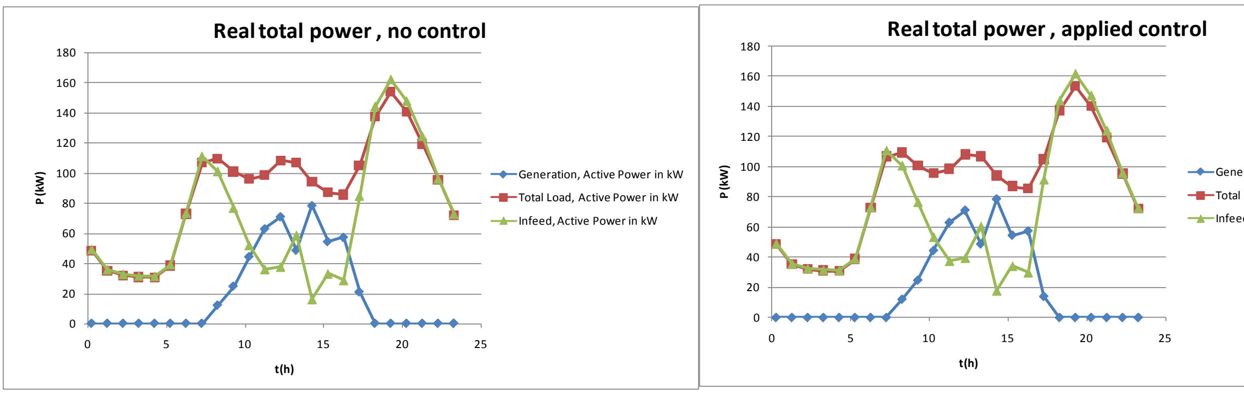



Figure 37: Overcast Real total power, comparing with and without transformer control

On the other hand, numerical data from power flows through the day says that total losses are reduced and total infeed is also reduced, so total losses go down. This is shown in Table 4.

| | Without capacitors | With capacitors |
|---|---|---|
| External infeed [MWh] | 106.86 | 105.93 |
| Generation [MWh] | 581.93 | 581.38 |
| Load [MWh] | 671.88 | 671.58 |
| Losses [MWh] | 16.91 | 16.15 |

Table 4: Reduction of losses 14March.

In the second source the line losses are reduced as total external infeed is showing.

Both sources match in the reduction of total losses.

### 4.4.4 POWER FACTOR CONTROL IN INVERTERS AND TRANSFORMER TAP CONTROL

The results are shown and explained.

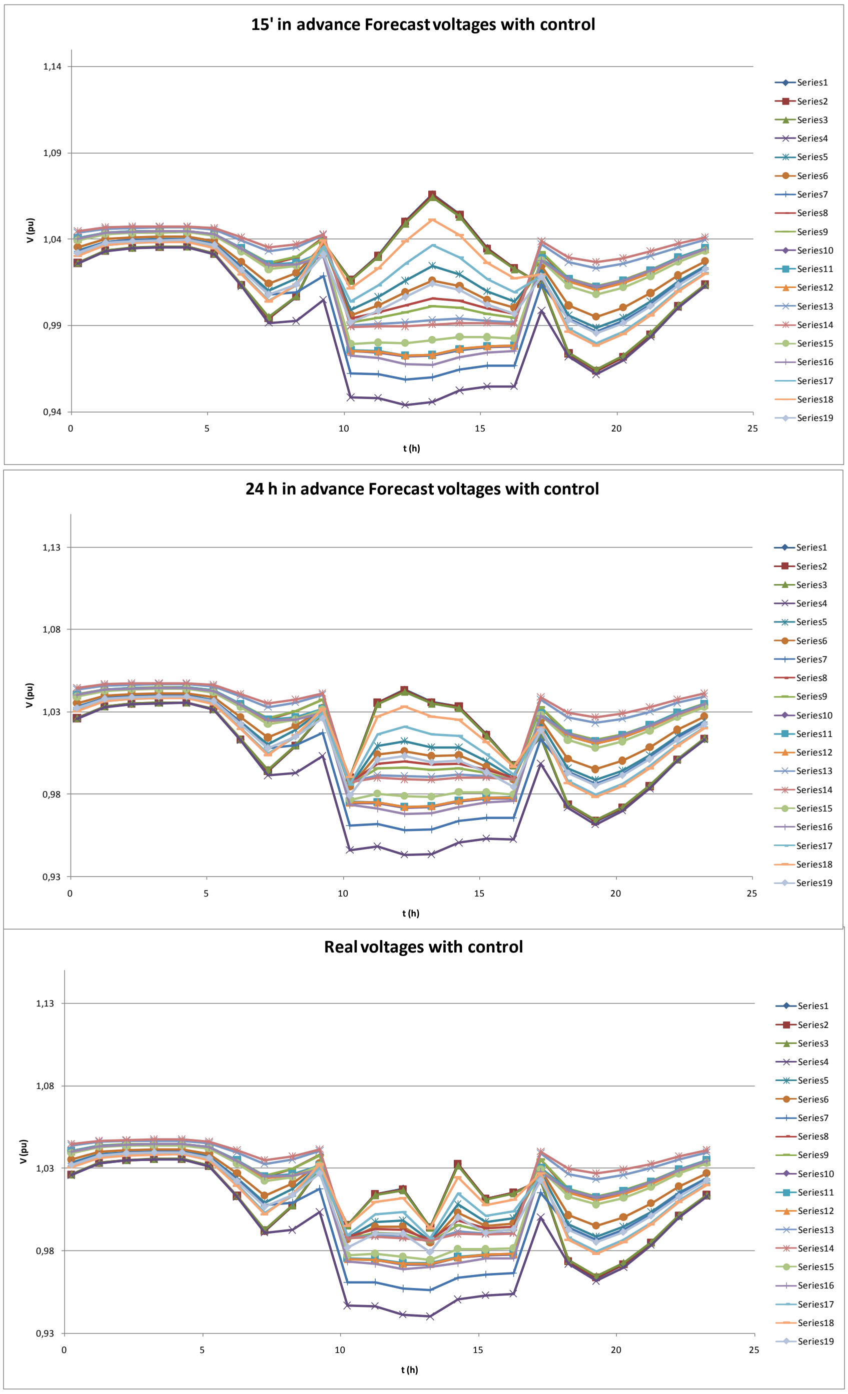



Figure 38: Overcast voltage profiles, with transformer & inverters control

This image shows the effect of the tap change in addition to the request to the inverter of every PV unit to control the power factor to 0.8 absorbing reactive power. This slightly reduces voltage locally because of load flow changes.

Looking at losses, a clear effect is shown: due to the reactive power consumption request of the inverters, the infeed current is higher, so losses across the grid are increased. As an example, the transformer losses are shown for the three predictions, with and without control in order to do an easy visual comparison. On the left side no control has been applied, and on the right side tap transformer and reactive power of the inverters consumption has been requested. The first line represents the results for the control applied to the forecast generation profile updated every 15 minutes, the actual losses in the second row and finally the forecasted losses due to the profile at 00 am.

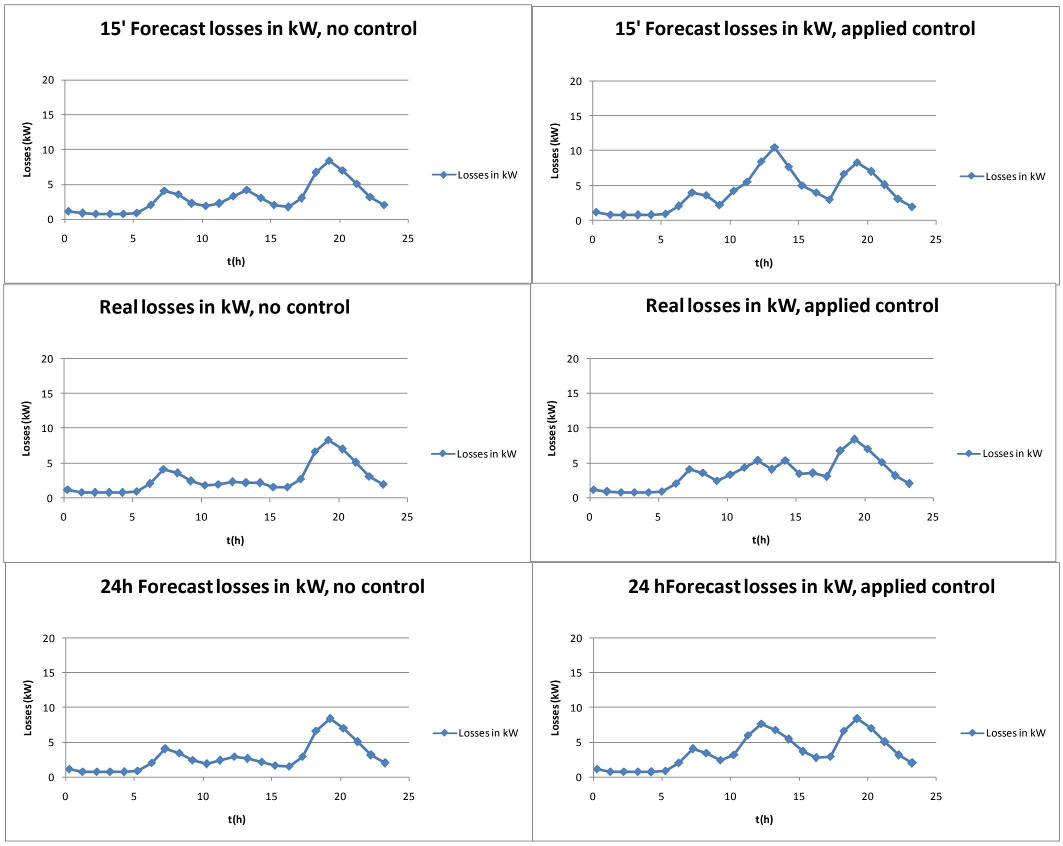



Figure 39: Overcast Losses for all forecasts in transformer & inverter control

In every forecast an increase of losses during control hours (10-16h) is clear. This measure ensures higher voltage control because of the capacity of inverters to generate or consume reactive power, but means higher losses.

## 4.5 UNDERCAST

This case refers to the profiles that previously appeared on Figure 12. This is a very interesting and critical situation, where both forecasts pointed out that generation would be much smaller than what it appeared in the actual situation. It can signify that control techniques to solve forecast problems are not aware of the real situation and may not act correctly, leaving problems unsolved.

### 4.5.1 ACTUAL PROFILE WITHOUT CONTROL

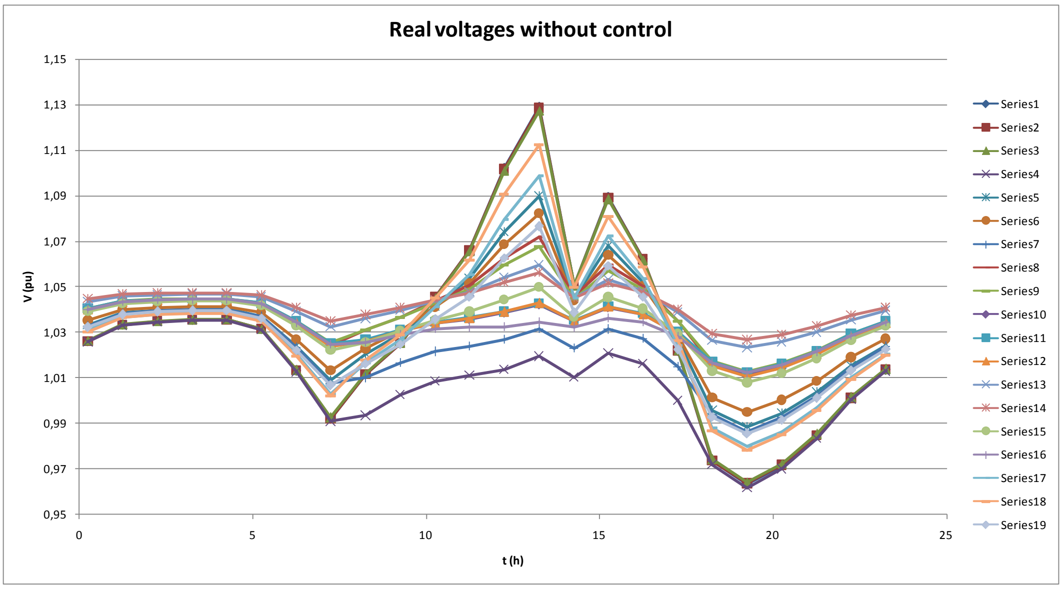



Figure 40: Actual voltages without control

Figure 40 shows the profile of the partly cloudy day that occurred on March 14th. This explains voltage variability and steep voltage surges. The peak is higher than was in the previous examples.

Due to the climate for that cloudy day, the voltages during the midday hours are very variable, because of the high dependency on PV for this case study. Note that voltage levels are not as high as they were in the previous analysis.

Analyzing the economic cost of overvoltage levels if no control measures are applied  with an analog procedure to the one in 4.3.1 results in -37,03€.  This quantity is proportional to the amount of nodes with voltage over its 5% nominal limit and the time this situation takes place. In absolute terms, it is an intermediate position between moderate and overcast scenarios.

Several figures are shown in order to explain the particular situation for these forecasts.

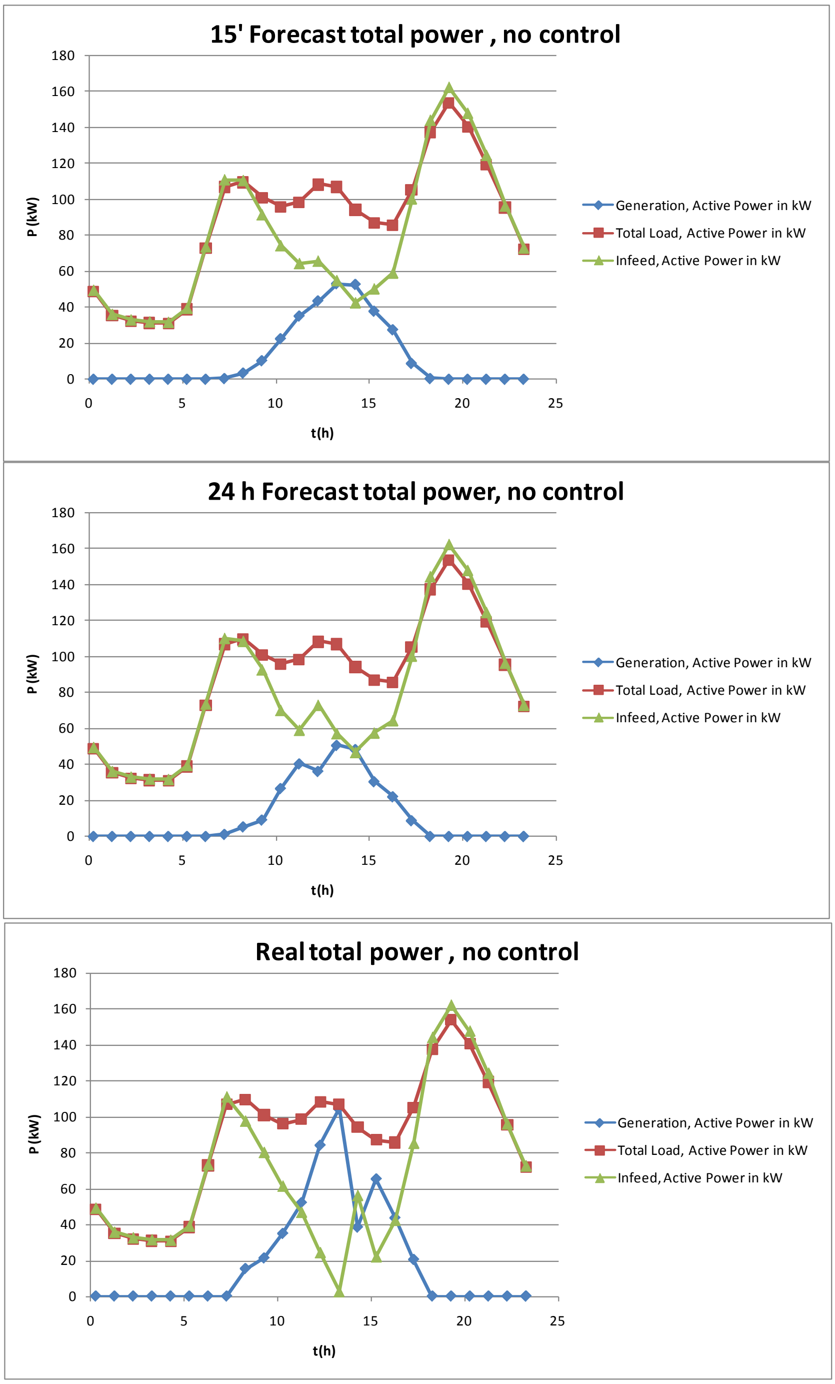



Figure 41: Undercast Real total power, without control

Figure 41 shows total active power from PV generation, total load and infeed. Note that peak real generation is approximately double than both forecast generation profiles. This could lead into a big mismatch and possibly into bad control decision making.

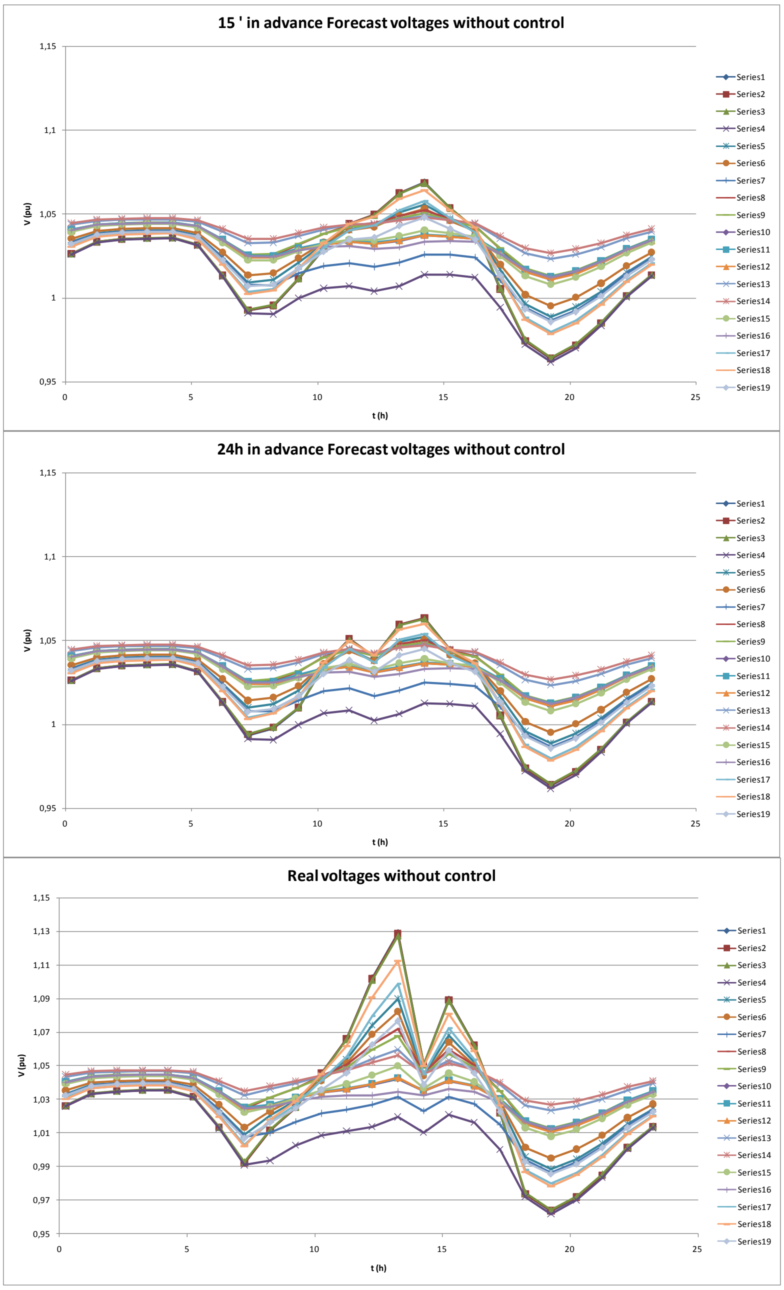



Figure 42: Undercast voltage profiles, without any control

## 4.5.2 TRANSFORMER TAP CONTROL

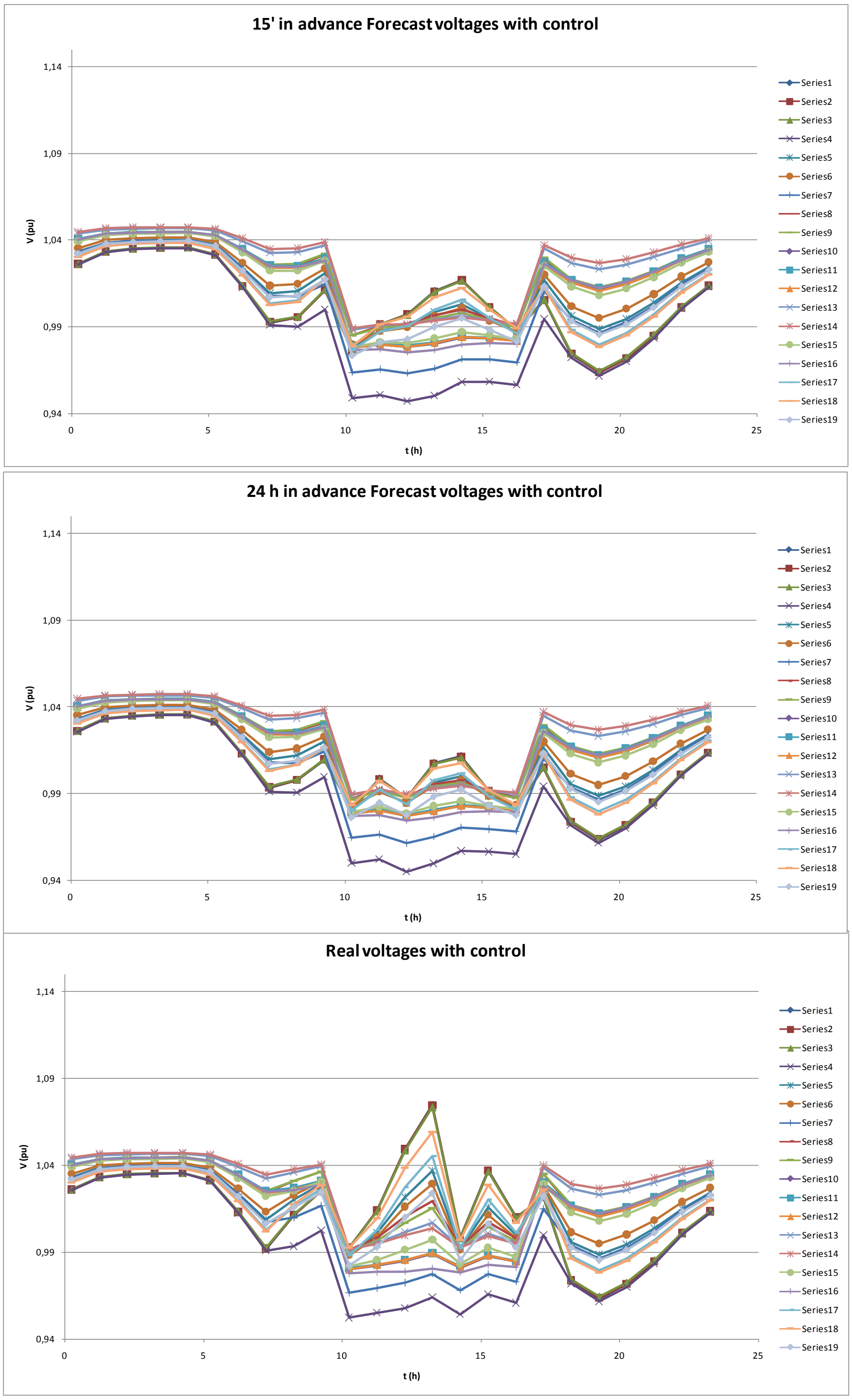



Figure 43: Undercast voltage profiles, with transformer control

Even though a mismatch between control actions analyzing the forecast and the real case could be a problem, for this particular case, both forecast situations suggest to lower the transformer tap one position, so there are no critical overvoltages in that situation.

Please note that the power generated is not as high as it would be in a clear day because of the clouds. As a consequence, the actual profile (bottom in Figure 42) suffers voltage levels over the limits in three nodes (1001,1002 and 1003)

This can be also observed watching Figure 43. Actual generation without control is on the left side, and with a tap reduction from 10 to 16 on the right side. It also details that the most critical hours are 12h and 13h.

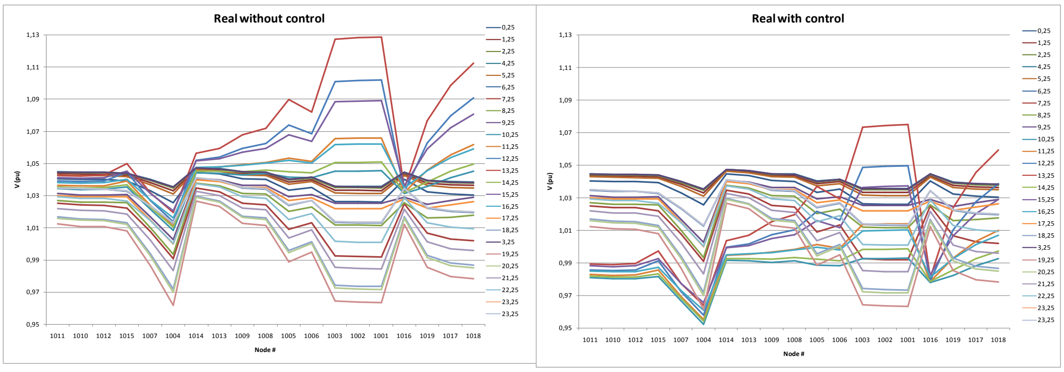



Figure 44: Undercast Real generation profile, comparing with and without transformer control

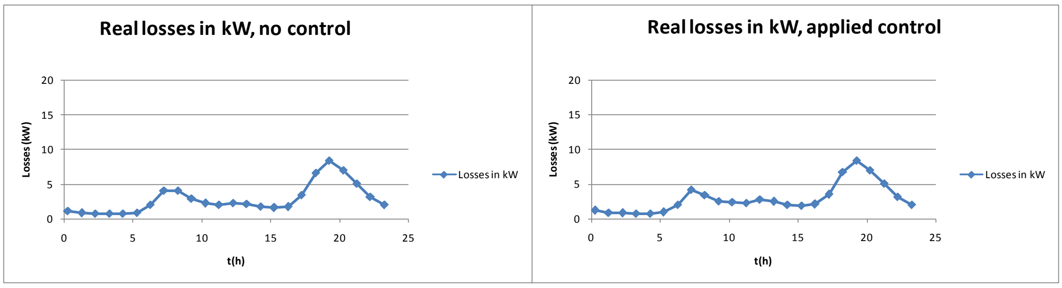



Figure 45: Undercast Losses in real transformer control scenario

Losses are mildly increased when the tap is reduced (right side) compared to the no control graph (left handside).

## 4.5.3 CAPACITORS AND TRANSFORMER TAP CONTROL

In this section, analogue to the other passive voltage controllers, the effect on voltage levels and losses is analyzed.

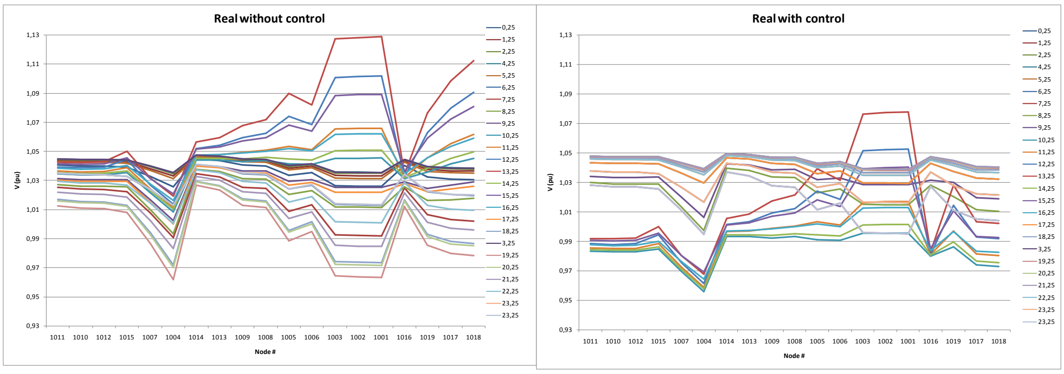



Figure 46: Undercast Real generation profile, comparing with and without transformer & capacitor control

Figure 46 is as expected very similar to Figure 44, with a slight increase in voltage levels, thanks to the reactive power injection.

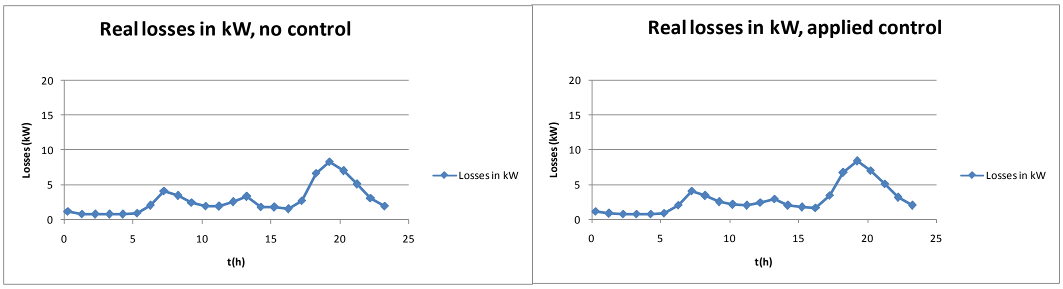



Figure 47: Undercast Losses in real transformer & capacitors control scenario

This figure shows a small reduction of losses that can be appreciated in the midday peak with this control technique. As it has already been explained, power factor correction can reduce losses.

### 4.5.4 POWER FACTOR CONTROL IN INVERTERS AND TRANSFORMER TAP CONTROL

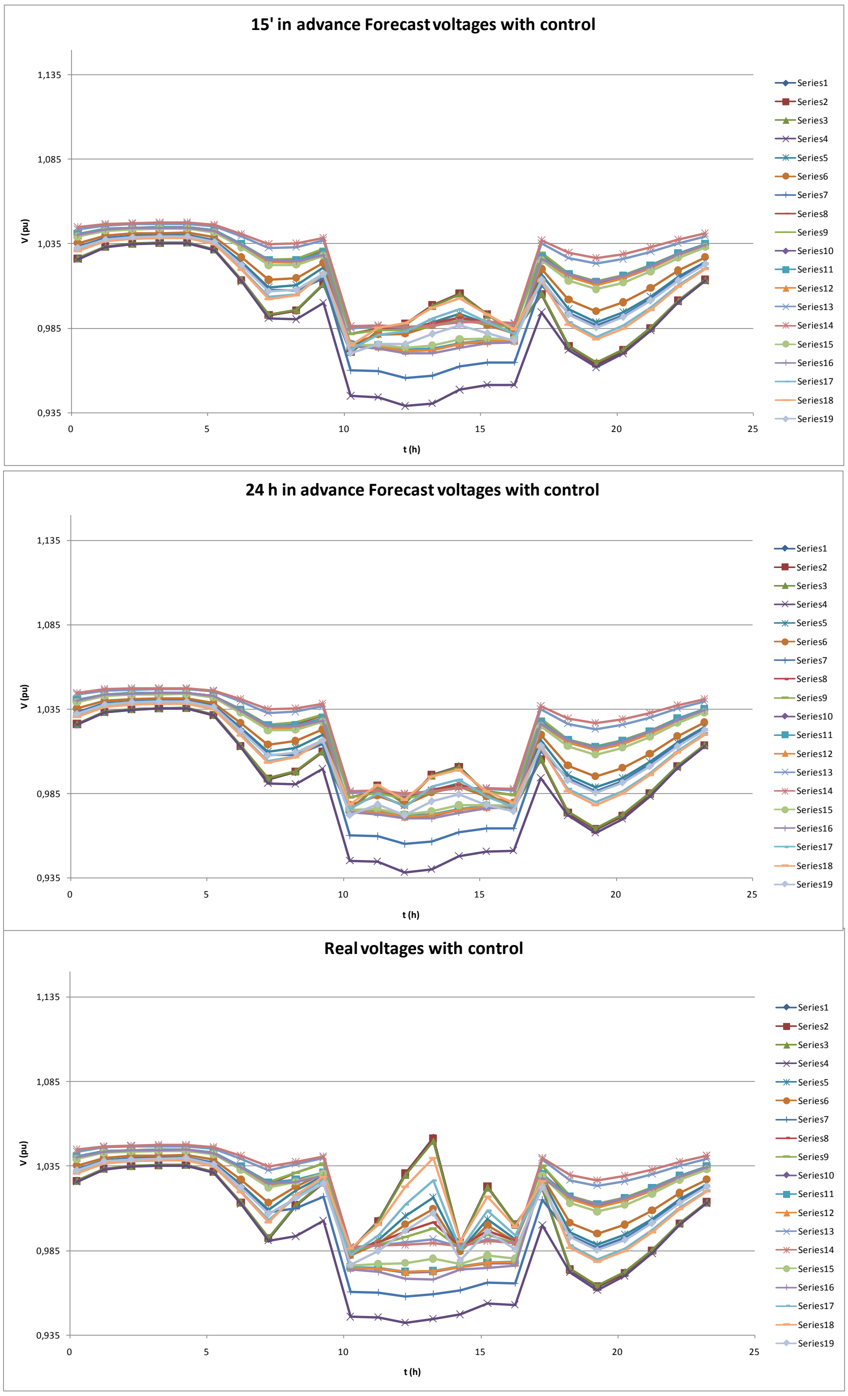



Figure 48: Undercast voltage profiles, without transformer & inverter control

In Figure 48 and Figure 49 it can be seen that controlling the power factor of every PV unit and lowering the transformer tap would solve the voltage problems even in the most critical situation, that in this case is the actual profile.

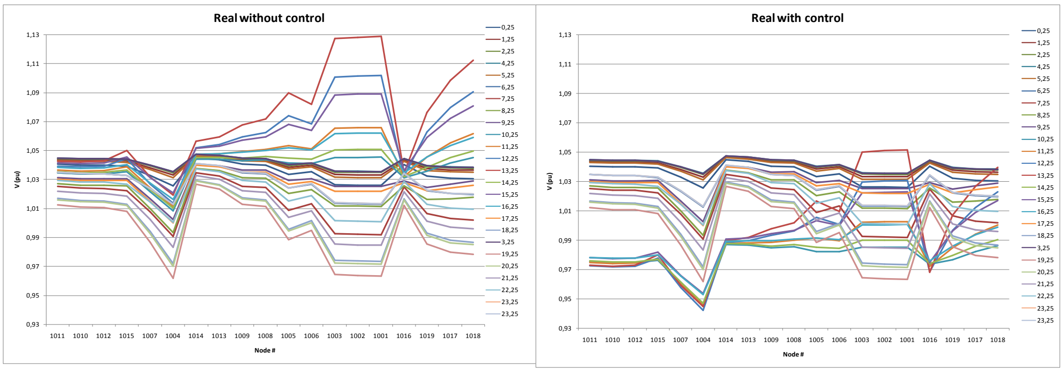



Figure 49: Undercast Real generation profile, comparing with and without transformer& inverter control

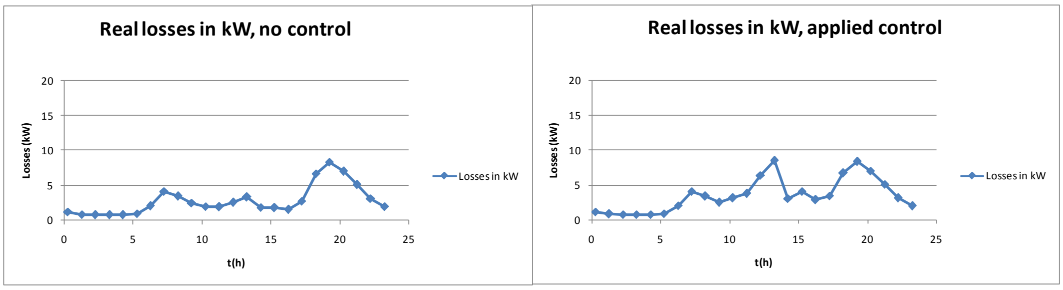



Figure 50: Undercast Losses in real transformer & inverters control scenario

The already introduced con is that losses clearly increase when the PV unit is required to absorb reactive power in order to decrease voltage locally. This means that current through the lines will rise and losses through the lines will increase in quadratic proportion.

# Chapter 5 CONCLUSIONS

The rural network has been modeled with DigSILENT software tool and several investigations with different PV penetration levels have been carried out. For certain PV generation, data related to voltages and losses have been obtained, exported and analyzed.

After the analysis with the overvoltage and losses problems were shown, a list of control measures were defined. The most effective and accessible ones were chosen and applied, cumulatively, trying to solve the problems. This has been fully achieved in a perfect information scenario, where control applied has demonstrated to solve different overvoltage situations.

Finally, the impact of PV generation forecast and its associated error in this rural network was investigated.

## 5.1 EFFECT ON VOLTAGE LEVELS

Regarding voltage levels, three real examples where displayed, and conclusions change depending on the forecast scenarios:

- For the penetration level imposed, if no control measures are applied, the voltage quality is unacceptable. The economic translation of low quality voltage provided is considerably large. This suggests specific focus on every design regarding high PV penetration levels, and investigation of the optimal solutions for every case regarding control actions in the long term.
- In a clear forecast scenario, control acts in very similar way as a perfect information case, and control measures satisfy voltage conditions.
- For a moderate scenario, it should be taken into account that in this particular grid there are only overvoltage problems and in a precise period of time, normally from 10 am to 16 am, where energy production is higher. As control measures have been taken considering forecasts, that predicted higher production, in the end appears lower voltage levels than expected, so voltage conditions are satisfied.
- Finally, in an undercast scenario, the most critical point appears. It shows off more power than expected, so control measures are defined to solve

the forecast conditions that are in this case less demanding than the real situation. This drives to problematic situations, where there is an overvoltage related to the forecast error. If the difference is so big that it involves not taking a control measure that was supposed to be unnecessary, consequences for the quality of voltage in certain nodes might be harmful, and it could even be necessary to curtail some PV units.

This analysis shows the necessity of applying control measures in order to lower voltages and provide voltage inside its design and regulation limits for every point, including extremes.

## 5.2 IMPACT ON LOSSES

Regarding losses, capacitors were expected to clearly reduce them. Note that lines and loads were considered as resistive-inductive, and capacitors were chosen to reduce the reactive power demanded, so the current was decreased and losses through the lines and transformer were expected to go down. The results show no clear advantage of this. In some cases it ended showing a clear advantage, but in other cases savings were negligible and do not justify the investment in capacitors. This is due to the drawback of a voltage increase which is produced, and the power flow, both active and reactive, changes.

## 5.3 IMPACT OF FORECAST

There is a clear impact of the forecast error. The closer the forecast is to reality, the better the control techniques solve the problems. Having a very big forecast error might have negative consequences to the network, or at least to the operational planning.  This suggests that investigation on forecast methods to increase its accuracy might be worthwile.

When looking into the reasons why the network was prepared to admit a considerable amount of generation without the need of any control measures, it was understood that there is also some margin due to the network oversizing design and economies of scale.

To sum up, a table with most relevant information regarding losses and voltage economic valuation is shown.

| NO CONTROL ACTIONS | Best control method | Losses | Voltage cost[€] |
|---|---|---|---|
| Moderate | - | 71,4 MWh | 51,3 |
| Overcast | - | 78,7 MWh | 29,4 |
| Undercast | - | 76,0 MWh | 12,04 |
| APPLIED CONTROL ACTIONS | | [Loss change compared to no control action] | |
| Moderate | Tr tap, capacitors on, inverters on cos=0,8 | +18,7 MWh | 0 |
| Overcast | Tr tap, capacitors on, inverters on cos=0,8 | +16,1 MWh | 0 |
| Undercast | Tr tap, capacitors on, inverters on cos=0,8 | +14,6 MWh | 0 |
| | | | |
| Moderate | Tr tap, capacitors on, inverters cos=1 | -1,8 MWh | 2,2 |
| Overcast | Tr tap, capacitors OFF, inverters cos=1 | +0,2 MWh | 0 |
| Undercast | Tr tap, capacitors on, inverters cos=1 | -0,4 MWh | 3,4 |

Table 5: Summary of results

The losses column shows in the first three rows the total losses of the network. In the “Applied control actions” rows, a positive number means increasing losses, and negative means reducing losses. The possible control actions, as explained before, are changing the transformer tap to a lower position, capacitors connected generating reactive power, and controlling the power factor of the inverters.

The table shows data for the actual profile, taking into account that control measures usually coincide, except for the case of two tap changes explained before, that it is chosen as the best control method.

Losses are doubled in case the inverters control power factor, but voltage problems are fully solved for each case. Depending on the target these two options are possible.

An intermediate possible solution might be to allow certain overvoltage levels, and try to reduce losses with the capacitor placement. This does not always achieve the desired objective due to the forecasting error and changes in the power flow. In case it did not improve results in the simulation, capacitors were disconnected.

# Chapter 6 FUTURE DEVELOPMENTS

Conclusions obtained from research and calculations open several paths to study. Some of them are listed and suggested:

Cloud effect: this is a problematic case which can lead to voltage surges and unexpected voltage transients. Having backup batteries might help reduce the problem.

Expansion of the current analysis, including more voltage dependency on load, frequency dependency, transient and short circuit analysis can be fulfilled. Additionally, more scenarios and seasonal variations could be taken into account, and load changes and starter load transients could be considered. Furthermore, control measures, such as batteries, FACTS, Automatic Voltage Regulators could be implemented to increase voltage quality and/or allow more PV generation to enter the network.

In addition, an in depth economic study, including more variables and market pricing to guide the distribution systems operators could be useful.

Finally, incentives for the distribution system operators and the consumers could be suggested in order to increase efficiency, mainly regarding loss reduction.

# Chapter 7 ANNEX

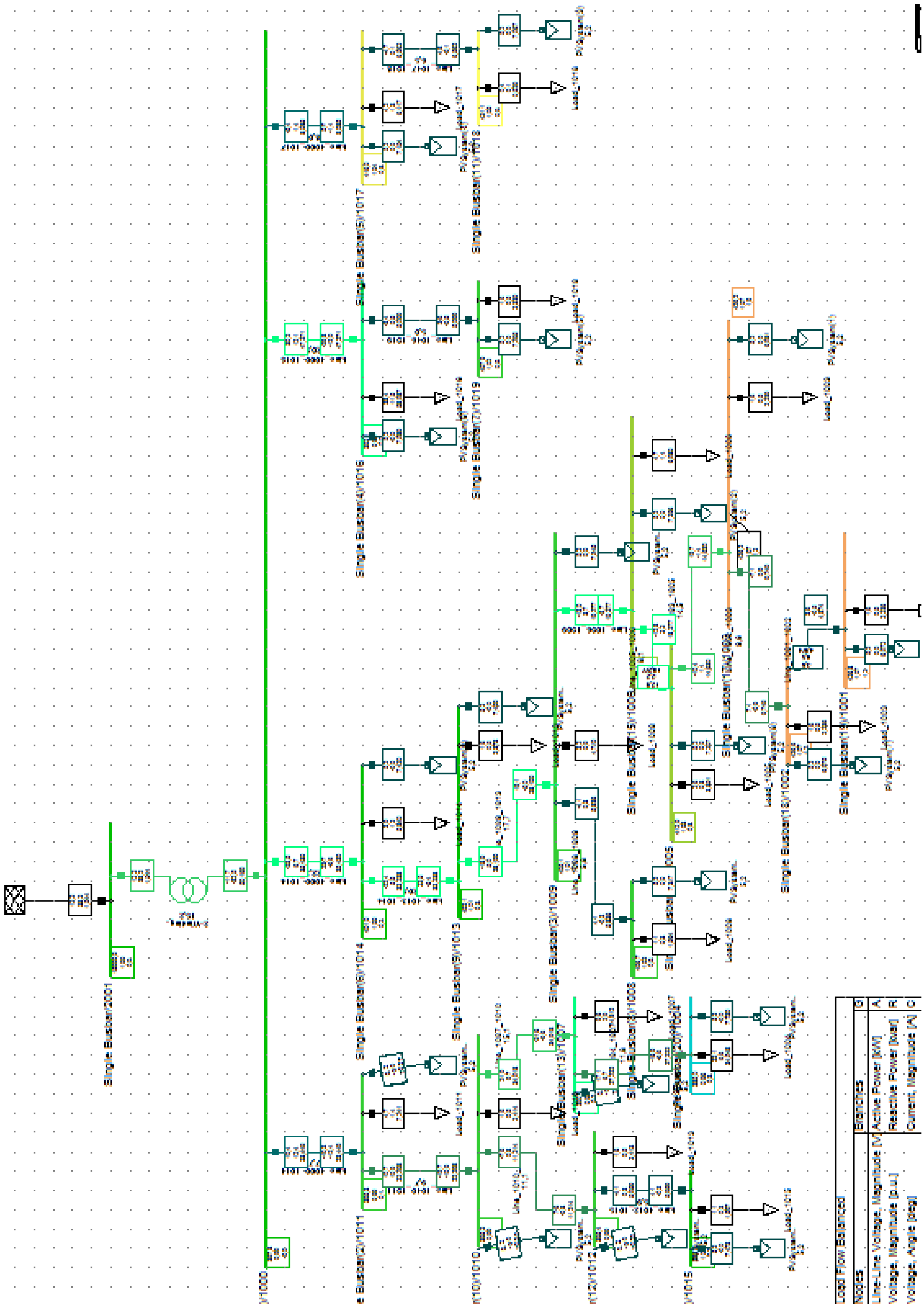


Figure 51: DigSILENT rural network overview

| Serie | Node # |
|---|---|
| 1 | 1011 |
| 2 | 1010 |
| 3 | 1012 |
| 4 | 1015 |
| 5 | 1007 |
| 6 | 1004 |
| 7 | 1014 |
| 8 | 1013 |
| 9 | 1009 |
| 10 | 1008 |
| 11 | 1005 |
| 12 | 1006 |
| 13 | 1003 |
| 14 | 1002 |
| 15 | 1001 |
| 16 | 1016 |
| 17 | 1019 |
| 18 | 1017 |
| 19 | 1018 |

Table 6: Series and nodes correspondence

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