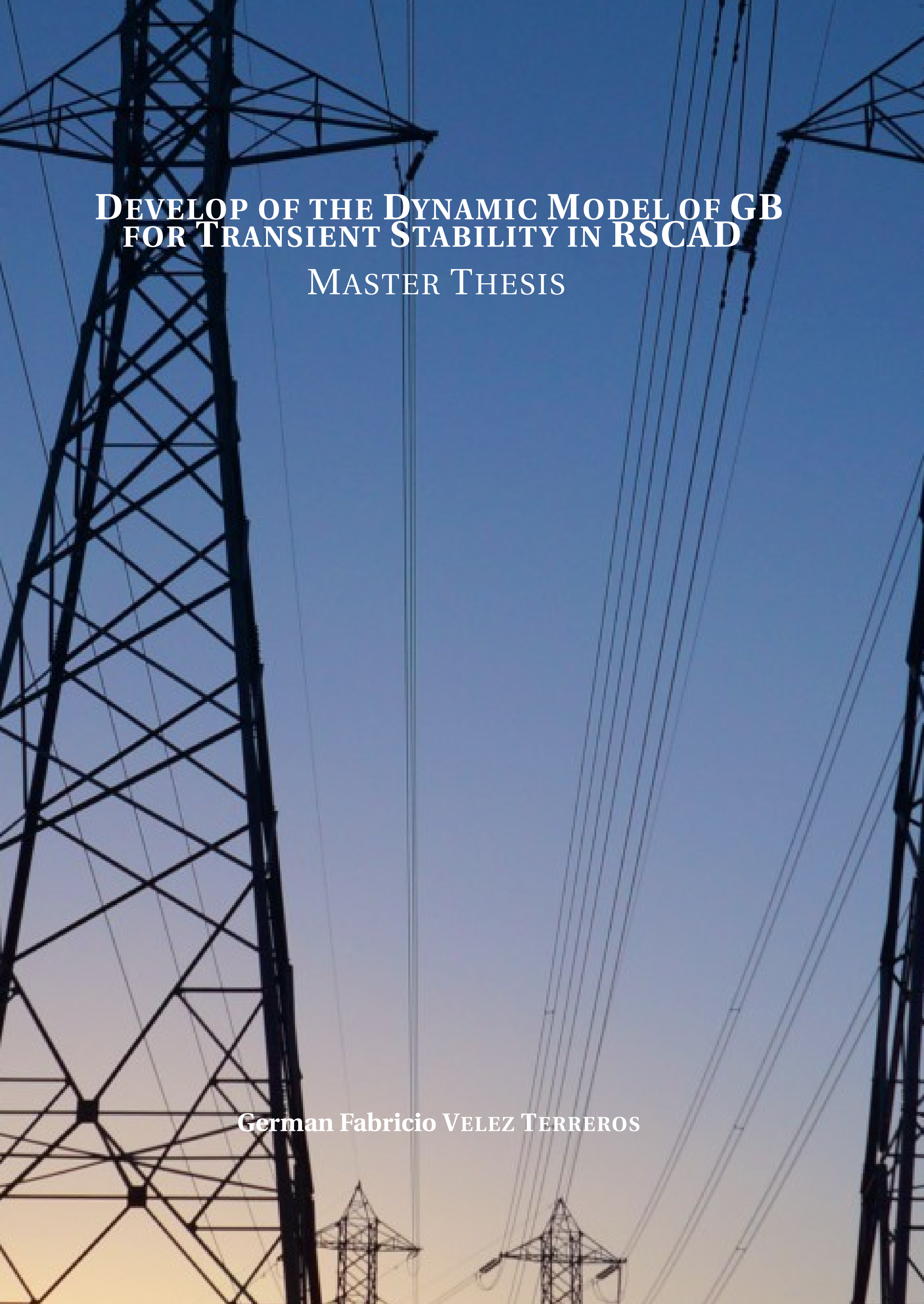

Develop of the Dynamic Model of GB for Transient Stability in RSCAD

Master Thesis

German Fabricio Velez Terreros

DEVELOP OF THE DYNAMIC MODEL OF GB FOR TRANSIENT STABILITY IN RSCAD

MASTER THESIS

by

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in partial fulfillment of the requirements for the degree of

Master of Science
in Electrical Engineering
(Electrical Sustainable Energy)

at the Delft University of Technology,
to be defended publicly on Monday August 22, 2017 at 10:00 AM.

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	Dr. Armando Rodrigo Mor

An electronic version of this dissertation is available at
http://repository.tudelft.nl/.

Life is like an infinite road with no end; you decide to walk through or stand on the roadside. When you find someone who goes in the same direction, never let it go. This project is dedicated to my family who supports me in every project, my new and old friends, and in special to my road companion my wife Ana...

Fabricio Velez

Acknowledgment

I would like to express my gratitude to the University of TU Delft for allowing me to continue my Master studies; It has been a challenge and a pleasure to be here. In addition, I would like to express my gratitude to Dr. ir. Jose Rueda. Throughout this two years, you have been a mentor. And during the thesis project, your guidance has been essential for accomplishing this work. Next, I would like to express my gratitude to Prof. dr. P. Palensky for your valuable feedback which helps me to improve my work. Last but not the least, I would like to thank Dr. A. Rodrigo Mor for accepting to be part of the thesis committee. Finally, I would like to thank the scholarship program by the Secretariat of Higher Education, Science, Technology and Innovation of the Republic of Ecuador who provided me with financial support for conducting my master studies at the University of TU Delft.

Abstract

Increasing wind generation causes displacement of conventional power plants with Synchronous Generators in electrical power systems. This condition leads to less inertia, less controllability and a degraded damping performance in the electrical systems. Studies of stability of the power system attempt to analyze this issues. Rotor angle stability studies using real time digital simulation requires the use of data mining to obtain an insight about the coherency of the system with the variation of the time series data. However, the limitations of the simulation systems as well as the magnitude of the models can lead into difficult study scenarios. By modeling the power systems in real time simulators, electrical studies can be performed faster than with conventional offline simulators. In this thesis project, the Britain baseline system was modeled in the Real Time Digital Simulator (RTDS) using as a starting point and initialization reference, the electrical power model developed for the simulator Power Factory. The model then was reduced using coherency analysis by clustering time-series-data. The same modeling considerations were applied for implementing future scenarios of the GB in the RTDS. For reduction purposes, three main areas describing the North, Central, and South parts of the system were considered in the GB model. The results show that while the area of study is considered constant the other two areas can be replaced by the coherent areas. Thus, less use of racks is required for analyzing the model in the simulator. This study contributes to the analysis of the power electrical systems, by providing valuable insights in how to reduce electrical models for their study in the RTDS.

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1

INTRODUCTION

1.1. INTRODUCTION

For the future years, several changes are expected in the electrical power system of Great Britain (GB)[4]. One of the changes involves the installation of wind generation for supply future energy demand the zones. However, with the increasing installation of wind generation, a displacement of conventional power plants with synchronous generators is expected. As a response to this change of generation in the GB area, less inertia and controllability will be presented in the power system leading to stability problems[5]. In order to deal with future stability issues caused by the replacement of generation and the interconnected nature of power systems, it is necessary to perform studies of the stability of the systems in the present using expected scenarios for the future. In the GB system, several studies have been performed in order to analyze the behavior of the system. Moreover, different electrical models have been developed to perform different kind of studies; One of the studies and the focus of the present project is the electromagnetic transient (EMT) phenomena, caused by faults, switching operations, load fluctuations and lightning strikes which causes transients in the system[5]. Due to the fast nature of this phenomena, not only a specific model has been required but also a specific simulator with enough processing capacity to deal with this phenomena. Real Time Digital Simulator (RTDS), is a powerful software/hardware simulator developed to the study of EMT in electrical power systems. In the present thesis project, the electrical power model of the GB system will be implemented in the RTDS to perform future studies in the network. EMT studies in the GB system involves a considerable high use of hardware resources of the RTDS. Due to the limitations of the RTDS acquired for the university of TU Delft and considering the parallel projects using the RTDS, it is required a reduction of the system after implemented.

The RTDS system installed in TU Delft has six racks used to deal with the simulation of the electrical projects. When implemented the GB system, it consumes four racks leaving only two available racks for the rest project. The reduction of the system must allow reducing the consumption of the racks of the RTDS while maintaining the behavior of the zones of the GB system. One way to deal with the reduction of the electrical power system is to find generators which have similar behavior when disturbances are applied to it. Thus, generators with similar behavior can be clustered and the system can be reduced.

Clustering analysis has been used to form groups of elements which oscillate similarly when subjected to disturbances. There are several techniques to cluster different signals. Indeed, time series data can be used to group elements of the electrical system. Once determined the number of clusters and the elements which are part of it, the aggregated elements can be represented as an equivalent of the group. These equivalents allow the reduction of the size of the system when the study conditions require it.

With the reduction of the network, it is possible to work with fewer areas. Indeed, it allows focusing on determined areas while maintaining the rest of the system as equivalents maintaining the performance of the original system. RTDS does not provide an eigenvalue analysis tool included in the software. Due to, the manipulation of time-series data is extracted from the RTDS and send to Matlab in order to find the clusters of generators which will lead to a reduction of the system.

The output of the project will provide the GB model and the future scenarios implemented in the RTDS. Additionally, the algorithms developed in Matlab for the Coherency analysis. Finally, the insight for reducing the model in order to use fewer resources of the RTDS.

1.2. LITERATURE REVIEW

In the study performed by [6], a method for dynamic reduction of power systems is proposed, similar projects identifying generators coherent generators were presented by [7], and [8]. Next, two branches of the study appear for determine the coherency of the systems as shown in the book [9]. One of the studies uses a modal-based approach as shown in the book [10], and the studies conducted by G. Troullinos in [11], [12], and [13]. And the other type uses a measurement-based presented by [9] and [8]. The model-based studies require the use of eigenvalues and well known of the system topology. As the eigenvalue analysis requires the use of the state matrix [5] to perform the study, and the RTDS system does not allow to extract the state matrix at the moment. However, some studies indicate the possibility of extracting enough information from system files to externally build the state matrix [14], and using that information perform eigenvalue analysis [15]. Nevertheless, using the measurement-based with the time-series data extracted it is possible to perform the coherency analysis. In the book [9], a great distinction between the different methods to perform the reduction using this method are explained. Additional studies have been performed using graph theories [16], independent component analysis [17], and hierarchical clustering [18] with the incorporation of the PMU signals, among others. For the project, with the implementation of the GB in the RTDS, the mechanism selected for finding the clusters is the use of a hierarchical method. Different options involving the use of a hierarchical method for performing clusters of time-series signals are possible[19]. One of the oldest ways for performing the cluster assignation is the use of the kmean method[20] [21]. Using this mechanism based on the signals extracted from the RTDS[3], it is possible to perform a cluster assignation which will result in a reduction of the system.

1.3. PROBLEM DEFINITION

The continuously increase in demand of developed countries, added to the expectation of using renewable sources, set new strategies to provide solutions to the balance of electrical energy of the nations. It is expected for the next years an increment of wind generation in the GB zone. Nevertheless, with the increasing incorporation of renewable energy sources (RES), conventional power plants using synchronous generators have been displaced. This shift of generation brings several sustainable advantages such as the lack of conventional fuels dependability and the use of renewable sources. Although, it also produces challenges for the control and operation of electrical power systems.

Synchronous generators provide major contributions to keep the stability of electrical power systems in comparison to wind generators. These contributions are related to parameters such as inertia and damping. Both parameter values are considerably higher in synchronous generators than in wind generators. Indeed, synchronous generators also present a better control performance over the system.

Considering Areas with only synchronous generators is possible to analyze the behavior of the system. For big areas, transient stability analysis is focused on small portions of the net. Even though, for areas of the size of GB, it is necessary to reduce the models in order to analyze the network under different perspectives.

Develop a dynamic reduction of the system using real-time digital simulators, it is crucial to handle time-series data. Using this information, determine coherent areas for implementation of the GB system would be optimal. Data mining techniques could help to get insight about coherency variation using time series data. Then, a tool which allows to automatically handle data-series information in order to process and obtain coherency areas of the system is required.

1.4. BACKGROUND

GB system model was delivered to TU Delft as part of the MIGRATE project for the studies in the incorporation of wind generators in the GB system for the future years. Additional to the GB model, several scenarios were presented for future modifications in the dispatch and generators. The model acquired for the project is specified for the simulator Power Factory DigSilent. The model consists of 29 electrical zones distributed in the area of the GB. Indeed, this model is a reduction of the original system employed for power electrical studies. The first task in the master thesis project is to implement the 29 zones model in the RTDS acquired for TU Delft. The RTDS consist in a simulator which incorporates software and hardware to perform EMT studies. With the aim to get into account with the RTDS, a first model was implemented using to study the Kundur two area model. Once implemented the model in the RTDS and Power Factory, an initialization parameters comparison was performed. The results demonstrate that both software simulators can provide the same initialization results when performed a power flow simulation. Both software is compatible as a first instance. Even though due to the magnitude of the GB system and the limitations explained in the next chapter, it is required a cluster evaluation with the aim of reducing the system to make possible future incorporations and modifications in the model.

1.5. OBJECTIVE AND RESEARCH QUESTIONS

The primary objective of the present thesis is to **develop a model of the GB system for the use in the RTDS software simulator**. The GB system took as a base is the one modeled in Power Factory Digsilent; it consists of 29 zones, and it will be specified in the next chapter. After implemented the model, reduce it using cluster methodology in order to allow different transient studies. The next research questions will be answered at the end of this project:

- How to ensure that power flow results and initialization obtained in power factory and RTDS are comparable?
- Is there any limitation in the RTDS for implementing the GB Model?
- How to reduce the GB system model in RSCAD while preserving acceptable accuracy?
- Is it possible to perform cluster analysis based on the time-series data from the RTDS?

1.6. RESEARCH APPROACH

Given the GB system as a model in the Power Factory, the first approach was to implement each element of the model in the RTDS simulator. Most of the elements were implemented following the same characteristics described in Power Factory. Nevertheless, wind generators and transmission lines require a more deep analysis. For the transmission lines, the model used in Power Factory differs with the model implemented in the RTDS due to the necessity of incorporating the parameter of distance for traveling waves model. While for generators, even though wind generators are already available in the library of the RTDS, their use requires more processing effort and the models of the GB system are still under development. Due to, wind generators were replaced by synchronous generators in the RTDS.

Once implemented the GB model in the RTDS, an initialization analysis will be performed comparing the power flow of both simulators. With the system implemented, the requirement of reducing the system for future element addition is recognized. A set of disturbances is implemented in the GB system for different conditions. This disturbance will produce the responses of different electrical parameters of the generators to perform the clustering assignations.

The clustering analysis will be performed by the use of the time-series signals simulated in the RTDS. The extraction of the signals required will be performed running scripts developed in the RTDS environment, to later import those signals to Matlab. Matlab is a powerful tool used in the treatment of signals for their analysis. Due to the facility to import signals to it and the implemented tools for hierarchical clustering, it was selected to continue with the second part of the project.

In Matlab, the signals are processed using a hierarchical cluster analysis by the use of kmean method, once defined the number of clusters per event. An iterative process is commanded to determine the cluster assignation of each zone to the convenient cluster. The last analysis will be performed by the division of the system into three main areas when keeping one area as constant named area of study, the other two areas will be replaced by coherent areas.

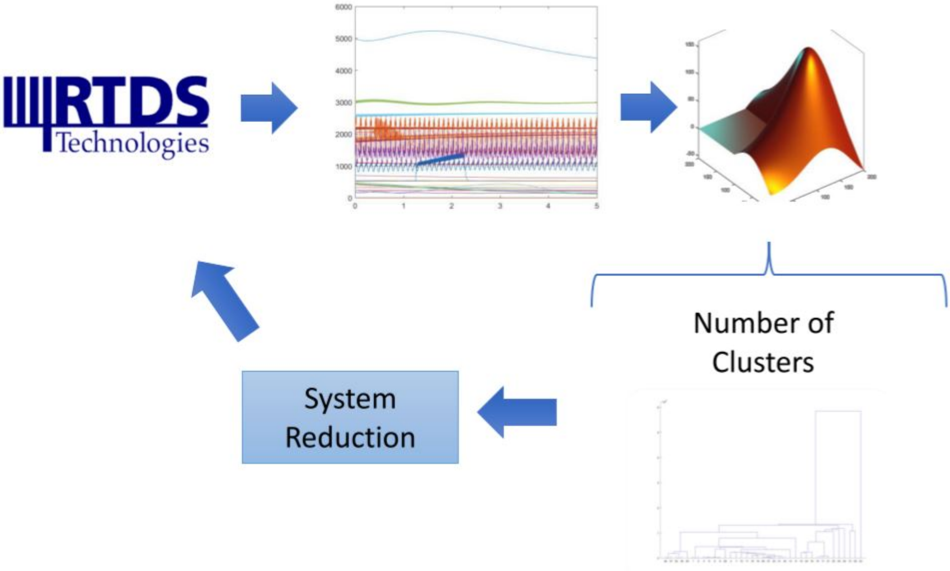


Figure 1.1: Research flow

Figure 1.1 represents the main steps conducted in this master project. First, the implementation of the GB system in the RTDS. Second the execution and export of the time-series signal when disturbances are implemented in the network. Next, the determination of clusters by performing the coherency analysis in Matlab. Finally, the insights to perform a reduction of the system maintaining an area of study and the coherent areas.

1.7. OUTLINE

This project is presented following the subsequent structure: The first chapter is reserved for the introduction and set the goals and research path for the entire project. Chapter 2, starts with a description of the model and the system where it will be modeled. Chapter 3, execute the comparison between simulators based on the initialization parameters and present the limitations of the program. Chapter 4, talks about the network reduction, from extracting the information from RTDS to use time-series data to cluster the elements. Chapter 5, present the results of the clustering and the GB model with specifications for studies. Chapter 6, detail the conclusions and recommendations of the project, plus possible applications for future work. Finally, the scripts and annexes are attached.

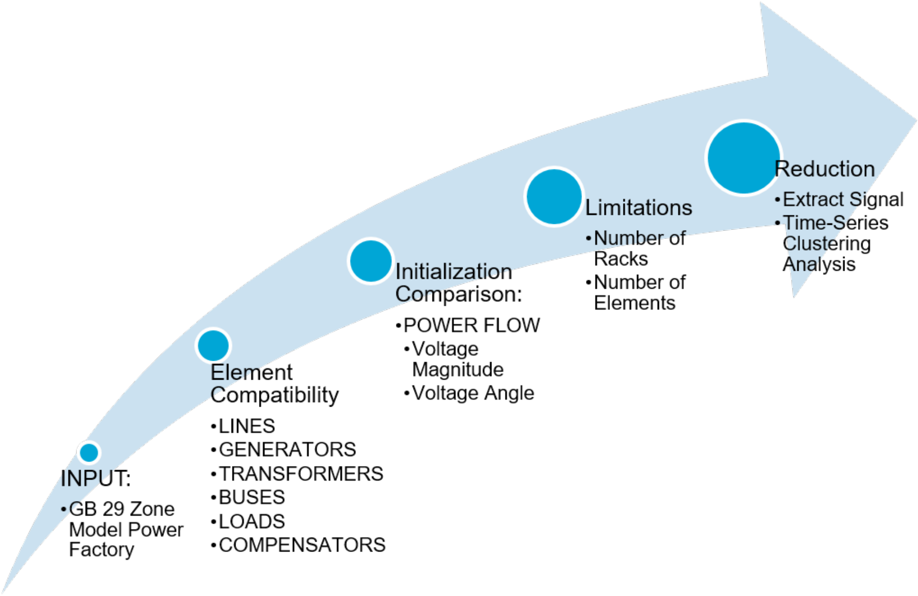


Figure 1.2: Thesis Work Flow

2

GB MODEL IN RTDS

2.1. DESCRIPTION

The Great Britain (GB) model already implemented in Power Factory consists of twenty-nine zones interconnected by nineteen nine transmission lines with one single circuit and forty-nine double circuits. This representation was delivered to TU Delft as part of the Migrate project, and it represents the dynamic model of GB. In the model, north areas have a nominal voltage of 275 kV while the center and south areas have 400 kV. Parameters of each element (generators, buses, lines, transformers, compensators, and loads) were specified for this model. Indeed, this model represents a reduction of the system; it could be confirmed analyzing the transmission lines, all lines have a length of one kilometer which is a representation performed for dynamic purposes.

Figure 2.1 shows the geographic GB model with the 29 zones distributed in their area. This image just describes an overall view of the system, the red lines are in 275kV, while the blue lines are the circuits in 400kV. It must be mentioned that this model does not represent any interconnection outside the twenty-nine zones.

Detailed information about the GB system, as well as their representation in the RTDS will be presented in this chapter. Table 7.2, reveals the values of parameters used to their model in Power Factory.

2.2. REAL TIME DIGITAL SIMULATOR

Real Time Digital Simulator (RTDS) is world's first real time digital power system simulator. It consists of two main components custom software and hardware designed for the study of Electro-Magnetic Transient simulations (EMT). The real time requires parallel processing in order to compute the state of the system during the time step defined. Time steps are in the order of 25μs to 50μs. One of the main advantages in comparison with other software simulators is the possibility of performing studies faster than with

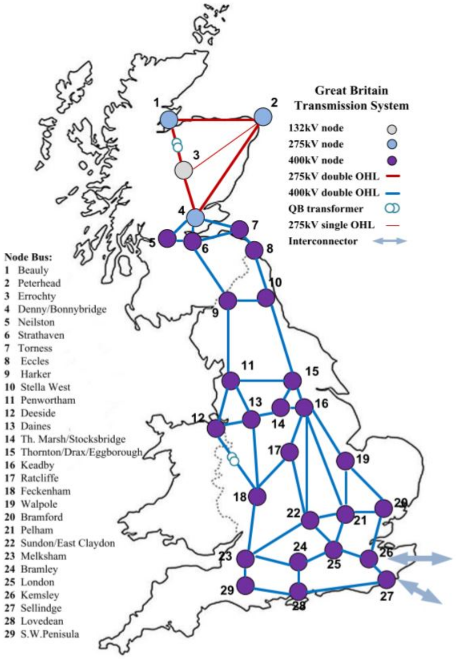


Figure 2.1: GB network representation of 29 Zones [1, 2]

offline simulators [3]. Even though RTDS is also used for closed loop testing of control components and protections, that characteristic will not be mentioned in the present project.

Another characteristic of the RTDS is the capacity of scalability due to the incorporation of new processors or elements according to the purpose of the final user. As the components are mounted to the network, several users can work in parallel to run different simulations. Hardware components and software description will be presented below.

2.2.1. RTDS HARDWARE

RTDS have a modular design, which allows the incorporation of more cubicles according to the necessities of the user. TU Delft has installed four cubicles, and in each cubicle are installed two racks. Main elements which are part of the rack are presented in figure 2.2. where:

GTWIF, is in charge of data exchange between the commands sent from the user to the system as well as the results from the system to the user. It makes possible the interconnection between six other racks via fiber optic. Moreover, It enables the parallel connections between hardware and workstations via Ethernet. PB5, this card allows to process the network solution; it can handle 72 single phase nodes and 100 single phase

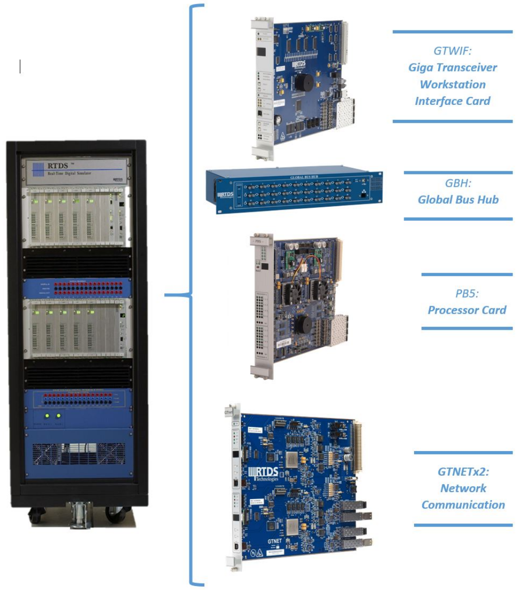


Figure 2.2: Rack Components

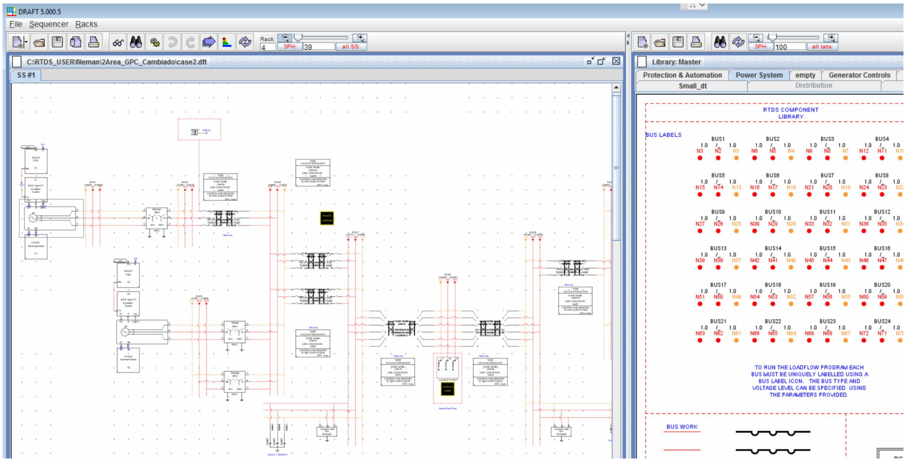
switches per rack. Nevertheless, the number of nodes can be doubled to 144 adding a second PB5 processor to the rack. GBH, it is in charge of keeping and handle the same time-step for the racks. Finally, GTNETx2, allows the communication with external devices and handle IEC 61850 protocol.

2.2.2. RTDS SOFTWARE

SOFTWARE: RTDS is formed by seven different modules which allow the system to build, design and run circuits. All these modules contain a graphic interface and a user-friendly manage. The use of the modules is related mainly to the finality of the user, even through Draft and RunTime modules are indispensables to create and execute simulations.

Draft Module: It is the environment to design the network, as well as other simulators the function of drag and drop is able. Single point connection or three-phase connections provide facility to interconnect elements. All elements are found in the library, and new libraries can be developed. In this module, the parameters of the system must be input, as well as the time step and the subnetwork division. Figure 2.3 presents the space for modelling at the left and the library at the right of the figure.

RunTime module and Multiplot, after designing the network another environment called RunTime allows executing the simulation. Moreover, control and export the results of the simulations. Additionally, it also offers a graphic editor to present the results in different ways. Included in this module, the possibility to execute scripts to start, stop and control of the parameter and elements of the simulation is enabled. These scripts are in C-programming language which makes easy the execution. Figure 2.4 represents a plot and controls for a circuit modeled in RTDS. FileManager module, it provides an organized way to keep different simulations. All archives created or imported are visible and accessible from this module. T-line module and Cable, it allows creating detailed models of the transmission lines, it is important to take into account that names of lines in draft mode must match the names from the t-line creation. Finally, CBuilder, it creates components under the requirement of the user. A graphical representation and control over the menus can be added.



TO RUN THE LOADFLOW PROGRAM EACH BUS MUST BE UNIQUELY LABELLED USING A BUS LABEL ICON. THE BUS TYPE AND VOLTAGE LEVEL CAN BE SPECIFIED USING THE PARAMETERS PROVIDED.

Figure 2.3: Draft Module in RTDS

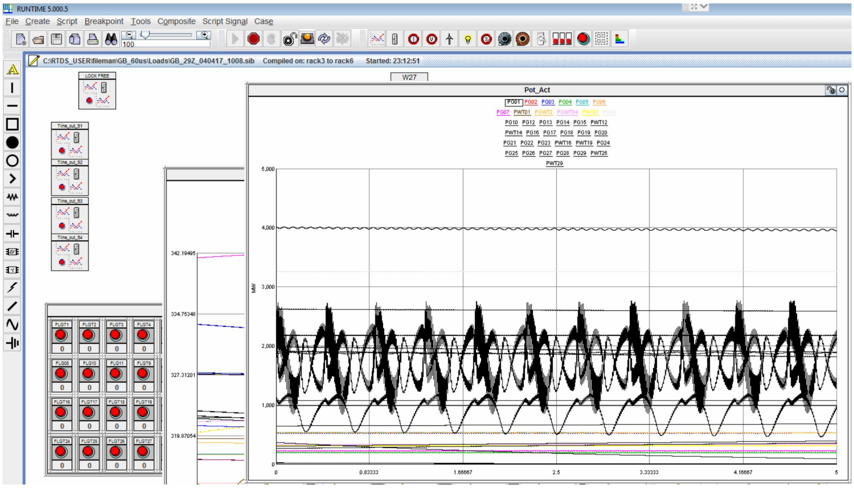


Figure 2.4: RunTime Module in RTDS

2.3. GB MODEL IN RTDS

The version of GB model which is considered as an input for this thesis is the one modeled in Power Factory. In the model, there are 29 interconnected zones representing the dynamic network behavior of the GB system. The first challenge in modeling the GB system in the RTDS is the lack of conversion tool from Power Factory to the RTDS. Due to, the system was modeled from scratch using the information available from the elements in power factory.

While implementing the GB system in RTDS several drawbacks and limitations appear. The limited number of racks and processors available in the system, the high processor consumption when modeling wind turbines and the size of the system does not allow a full implementation of the model in the RTDS. The next subsection will explain the limitations of the RTDS when conducted the project as well as the solutions and assumptions developed for overcoming the restrictions.

2.3.1. BASELINE

The model of the GB system in Power Factory was delivered to TU Delft as part of the Migrate Project. It consists of 29 electrical zones interconnected as presented in the figure 2.5. The baseline scenario contemplates a dispatch considering the actual elements which are part of the GB system. The baseline reflects a dispatch in the year 2016. The model with lines and voltage levels were extracted from the "Electricity Ten Year Statement 2016" from UK electricity transmission[4].

This scenario is the main focus of the project, the complete scenario will be modeled in the RTDS under certain restrictions and assumptions developed in this chapter. In the figure 2.5, each block represents an electric area mainly integrated by a bus bar, generators, loads, transformers, and compensators. The figure describes the size and interconnection in the GB network. A similar output will be obtained in the RTDS, with the use of subsystem as detailed next. The dispatch, as well as the characteristics of the model, were extracted from the model in Power Factory. The table 2.1 presents the generation and load values implemented as a dispatch in the RTDS. Figure 2.5 presents the distribution of the zones in the GB system. Each zone corresponds to a substation, due to in each of the zones generators, buses, transformers, loads, and compensators are installed. In zones one, two and three, and four the voltage level is 275kV. In the rest of the areas, the voltage level is 400kV. Figure 2.6 is an example of how a zone is displayed in the RTDS. Additional to the elements of the substation, fault points and fault logic point must be added to allow simulate faults in the system. Fault points and logic will be explained later in the chapter.

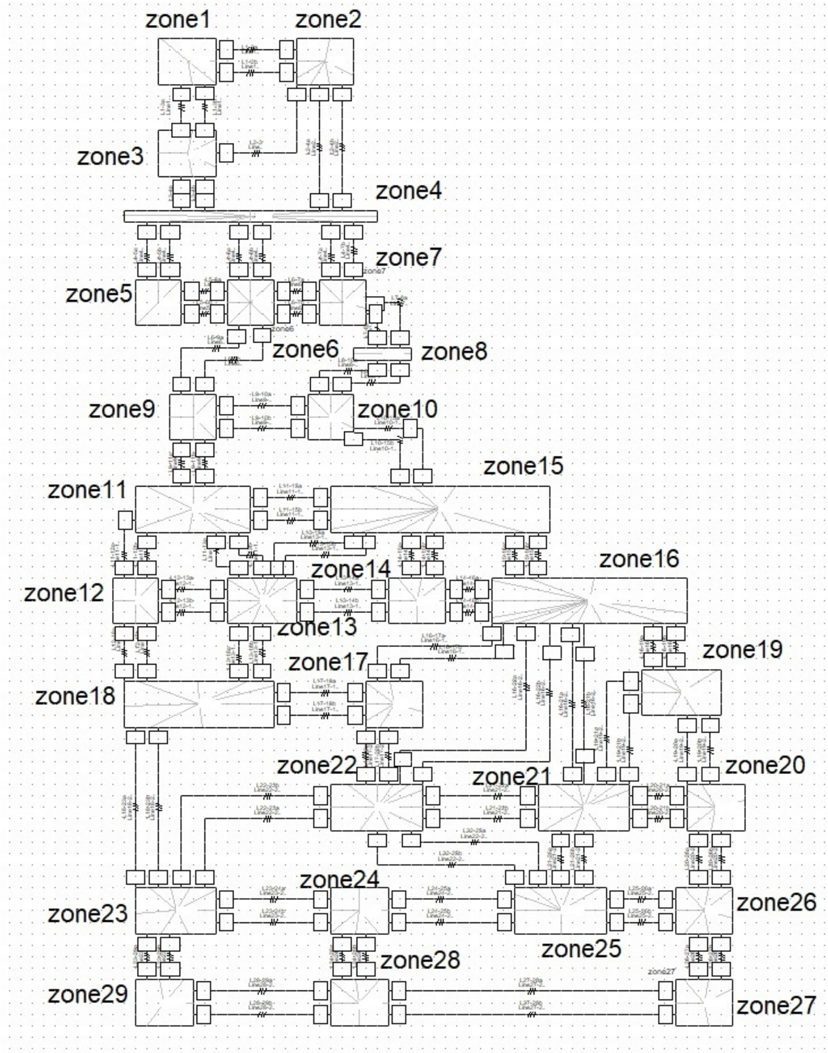


Figure 2.5: GB model in Power Factory [3]

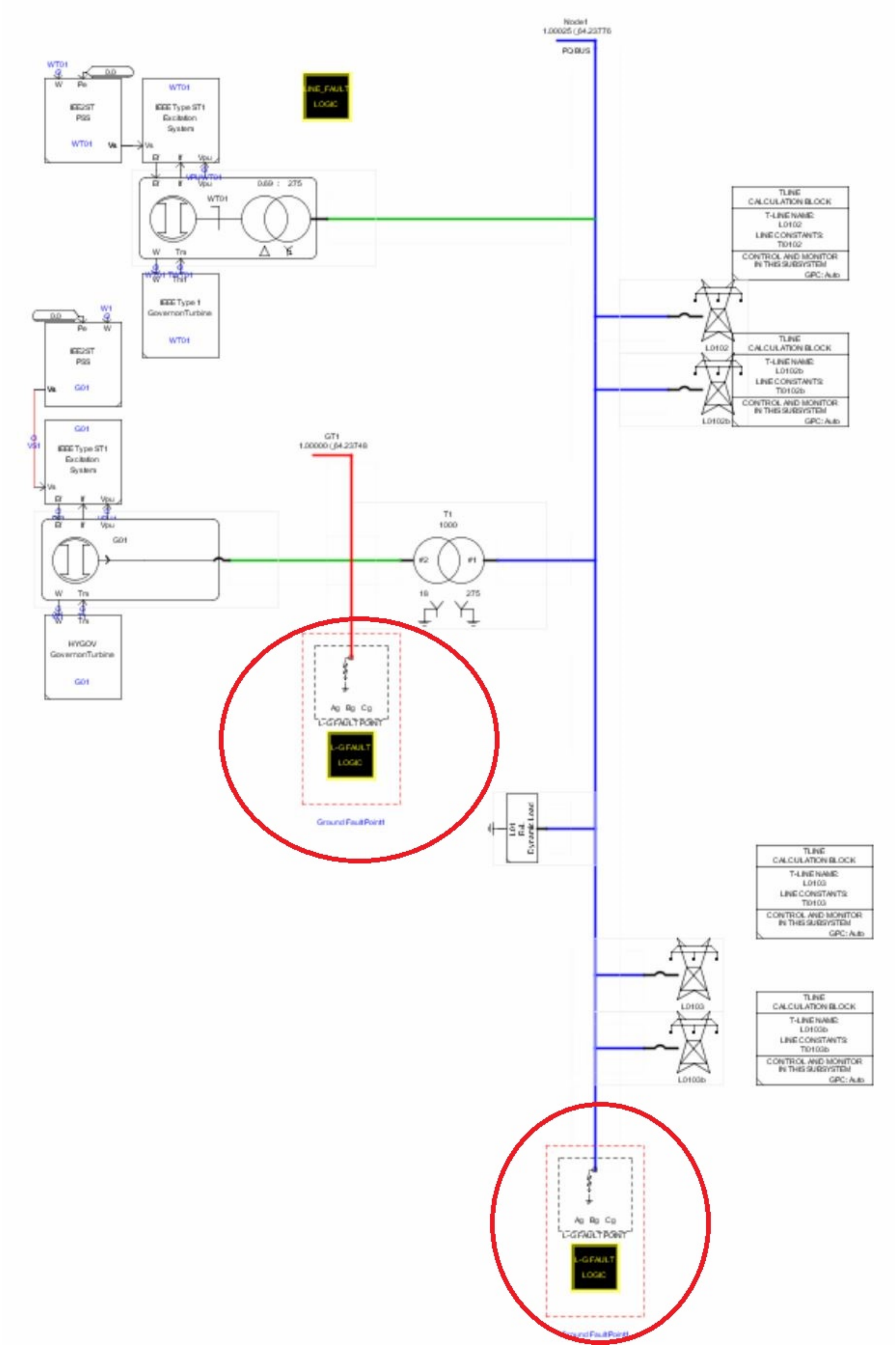


Figure 2.6: GB model in Power Factory [3]

Table 2.1: GB System Baseline 2016[4]

Baseline Case 2016							
Region	**Sub station**	**Syncho Generator (GW)**	**Wind Generator (GW)**	**Active Load (GW)**	**Reactive Load (MVAr)**	**Wind Generator Dispatch (GW)**	**Synchro Generator Dispatch (GW)**
Scotland	1	1.08	0.8646465	0.53	110.25	0.856	0.94374
	2	1.08	0.8684848	0.53	110.25	0.8598	0.94793
	3	1.08	0	0.53	110.25	0	0
	4	1.08	0.849798	0.53	110.25	0.8413	0.92753
	5	1.08	0	0.53	110.25	0	0
	6	1.08	0	0.53	110.25	0	0
	7	1.08	0.8512121	0.53	110.25	0.8427	0.92908
	8	1.08	0	0.53	110.25	0	0
North England	9	3.78	0.725	3.25	682.50	0.71775	0.79132
	10	3.78	0.725	3.25	682.50	0.71775	0.79132
	11	3.78	0.725	3.25	682.50	0.71775	0.79132
	16	3.78	0.725	3.25	682.50	0.71775	0.79132
West England	12	3.77	0.2	2.17	455.00	0.198	0.2183
	13	3.77	0	2.17	455.00		0
	14	3.77	0.2	2.17	455.00	0.198	0.2183
	15	3.77	0	2.17	455.00		0
	17	3.77	0	2.17	455.00		0
	18	3.77	0	2.17	455.00		0
East England	19	1.95	0.5495	1.88	393.75	0.544005	0.5997
	20	1.95	0.55	1.88	393.75	0.5445	0.6003
South England	21	1	0	2.06	431.67		0
	22	1	0	2.06	431.67		0
	23	1	0.497	2.06	431.67	0.49203	0.5424
	24	1	0	2.06	431.67		0
	25	1	0	2.06	431.67		0
	26	1	0.504	2.06	431.67	0.49896	0.5501
	27	1	0	2.06	431.67		0
	28	1	0	2.06	431.67		0
	29	1	0.4995	2.06	431.67	0.494505	0.54519

2.3.2. TRANSITION SCENARIOS

As extracted from the electricity ten-year statement 2016 [4], two different type of scenarios are developed fo the future of the GB system. These scenarios are centered on the expected behavior of the BG system for the coming years. Even though one of the focus points is to reach the 2050 carbon reduction target, one of the scenarios does not have high expectation in the increasing installation of renewable sources of energy. This scenario is called NO PROGRESSIVE and although consider new renewable installations, it does not consider that the increment will be drastic.

On the other hand, the second scenario called GONE GREEN proposes a series of policies interventions, as well as, innovations to reduce greenhouse gas emissions. This scenario assumes an investment of more money and more focus in the long-term green ambition [4]. Due to limitations in collecting information, the NO PROGRESSIVE scenarios will not be modeled in the RTDS. Moreover, the GONE GREEN scenarios will be implemented in the RTDS as well as the baseline model.

GONE GREEN scenarios present four future scenarios for the coming years 2020, 2025, 2030 and 2035. The replacement of synchronous generation, also the installation of more wind generation will describe the characteristics of this new scenarios. Table 7.4, table 7.5, table 7.6, and table 7.7 presented in the Annex 7.3: GONE GREEN TABLES, will present the dispatch and the type of generation for each of the future scenarios.

2.3.3. COMPONENTS

The 29 Zones of the GB system developed in Power Factory contain several elements to be modeled in the RTDS. Due to keeping the scope of the thesis to synchronous generators and the lack of wind generator models in the RTDS. An important assumption regarding the replacement of wind generators by synchronous generators is explained in this section. The rest of the GB system components are presented next to a small detail of the menus for modeling each element. The majority of the parameters were extracted from the Power Factory and implemented in the RTDS using as guide [3].

SYNCHRONOUS MACHINE MODEL

The RTDS Library offers several types of models for generators. Each of them has their own characteristics and are used depending on the type of generation and the properties required by the user. Figure 2.7, represent the model used in the RTDS, this model, as well as the model in Power Factory, correspond to the 7th order. The name of the generator is "RTDS_SHARC_MAC_V31", and can be located in the main library in the draft mode. Additional to the generator an exciter, governor, and PSS can be coupled.

For study convenience, the parameters of the Generator, as well as the AVR and Governor controllers were adjusted as close as possible to the elements from the Power Factory. Even though, all controllers can be modified in function of future studies. An advantage of using this model is that it has incorporated the possibility of automatically connecting a transformer at its output. The internally connected transformer not only reduce the number of connections, but also three single electrical nodes can be saved.

In most of the cases, this transformer was not used due to the limitation of only allow to choose a delta-Y connection for the transformer.

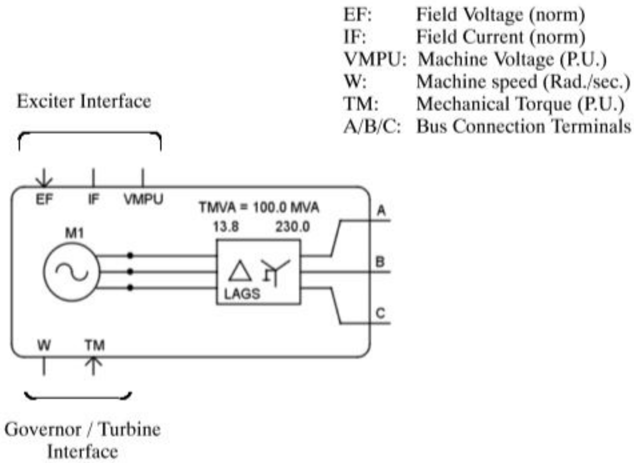


Figure 2.7: Synchronous Generator RTDS [3]

It must be taking in consideration the importance of the selection of signals for future plot and analysis. A complete guide for configuration of each parameter of the generator is presented in [3]. Parameters like apparent power, voltage and frequency were kept as the same as the parameters presented in Power Factory.

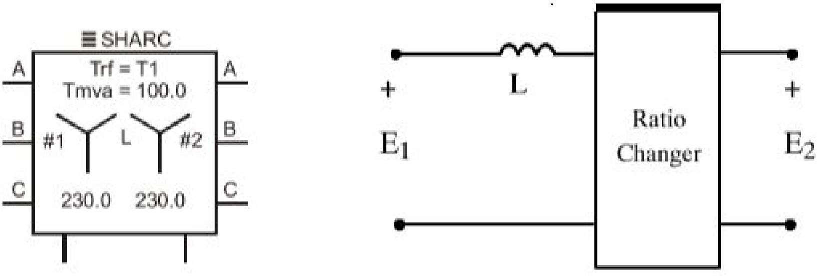
WIND GENERATORS

Wind Generators are part of the baseline model of the GB system for the year 2016. An important assumption was made with the wind generators. As the modeling of wind generators in the RTDS are part of a different study. It was discussed the possibility of representing the wind generators as synchronous generators with active power and reactive power constant. It was also discussed that inertia must be reduced in order to adjust as much as possible to the wind generator behavior. It is expected in future tasks the integration of wind generator model to the GB system in the RTDS.

TRANSFORMER

As well as Generators there are diverse types of transformers available in the library of the RTDS. The transformer selected is as similar as the transformer in Power Factory, the model in the library of the RTDS is the "TRF3P2W". It is a three phase two winding transformer model; it has three modes: ideal, linear and saturation. And it can be used in any of the modes depending on the information assigned as input. This transformer also has the possibility of addition tap changer. Even though no tap changers were modeled for the simulations.

For the simulations, the transformer was modeled as an ideal transformer, where the magnetizing inductance is neglected, and the only reactance take into account is the leakage reactance. RTDS also neglect the winding resistances; it assumes these as the value of zero. Figure 2.8a presents the symbol of the transformer in the RTDS where the winding configuration can be modified. Fig 2.8b is the representation of the ideal transformer used by the RTDS with no magnetizing path.



(a) Transformer Model RTDS (b) Ideal Transformer in RTDS

Figure 2.8: Transformer in RTDS [3]

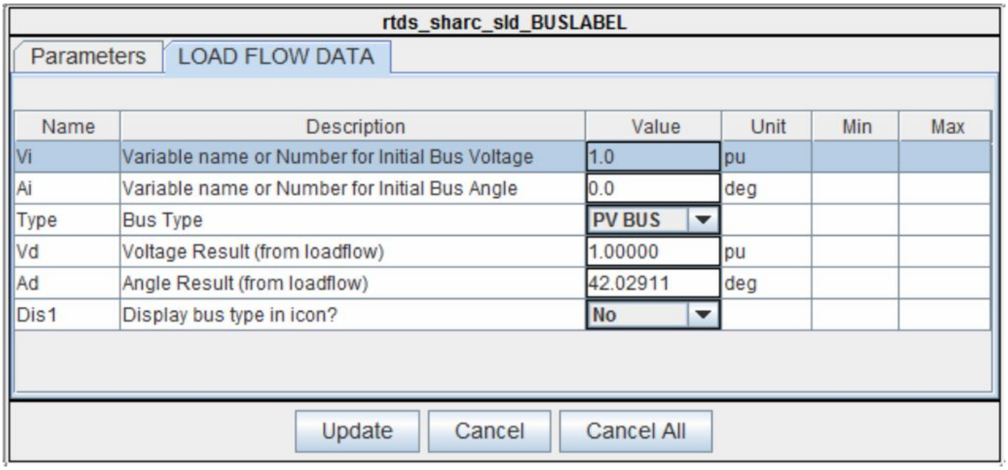
BUS BAR

There was no difference in the type of bus bar in the RTDS and Power Factory. The only difference is the way of each software to define the type of bus. while in Power Factory the type of bus is defined by the generator or load connected to it, in RTDS it is necessary to define the type internally in each bus. Figure 2.9, present the input menu for configuring a bus bar in the RTDS. The parameters Vd and Ad will display the values of the power flow result in voltage magnitude and angle when a power flow is run in the draft mode.

TRANSMISSION LINE

In RTDS there are two types of transmission lines available in the library, depending on the study to perform and the own characteristic of the lines to model. Travelling wave model and Pi section model represent the behaviour of transmission lines in the RTDS. Nevertheless, the different representation implies that PI model uses lumped parameters, while travelling waves uses distributed parameters. One of the advantages of using travelling wave models is the reduced processor consumption compared with the PI section model. Travelling wave models are also required in order to interconnect bus bars from different subsystems.

In the Figure 2.10, three elements are presented for a transmission line in the RTDS. The calculation block, where it is possible to define the type of transmission line, and the send and reception side of the transmission line. Using the PI model is plausible. Nevertheless, integration time step of the system must be taking into account. In order to work correctly, the travel time step defined for the transmission line must be at least



rtds_sharc_sld_BUSLABEL

Name	Description	Value	Unit	Min	Max
Vi	Variable name or Number for Initial Bus Voltage	1.0	pu		
Ai	Variable name or Number for Initial Bus Angle	0.0	deg		
Type	Bus Type	PV BUS			
Vd	Voltage Result (from loadflow)	1.00000	pu		
Ad	Angle Result (from loadflow)	42.02911	deg		
Dis1	Display bus type in icon?	No			

Figure 2.9: Bus modelling in RTDS [3]

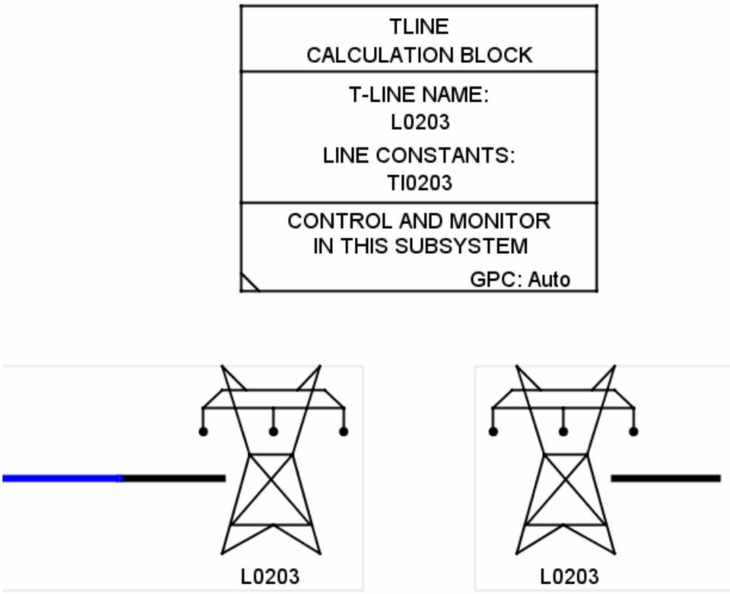
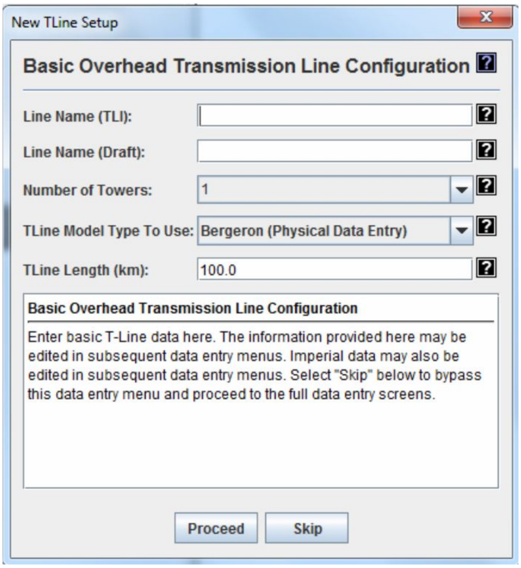


Figure 2.10: Transmission Line in RTDS [3]

equal to the single integration time implemented. It is compulsory to mention that all transmission lines distances in Power Factory were set as 1 Km, due to traveling wave models will be implemented the in RTDS and will be discussed in the next chapter. The final distances of transmission lines, as well as the equivalent parameters of reactance, capacitance, and susceptance, are presented in table 7.2.

Additional to the information provided in DRAFT mode of the RTDS, it is necessary to create transmission lines to input the parameters of the lines. RTDS use a complementary interface called "Tline setup". figure 2.11 and figure 2.12 present the interface were the electrical parameters of the transmission line must be entered. RTDS allows to input physical information about the lines and configuration; Even though, it will not be used for the GB model.


New TLine Setup

Basic Overhead Transmission Line Configuration

Line Name (TLI):

Line Name (Draft):

Number of Towers: 1

TLine Model Type To Use: Bergeron (Physical Data Entry)

TLine Length (km): 100.0

Basic Overhead Transmission Line Configuration

Enter basic T-Line data here. The information provided here may be edited in subsequent data entry menus. Imperial data may also be edited in subsequent data entry menus. Select "Skip" below to bypass this data entry menu and proceed to the full data entry screens.

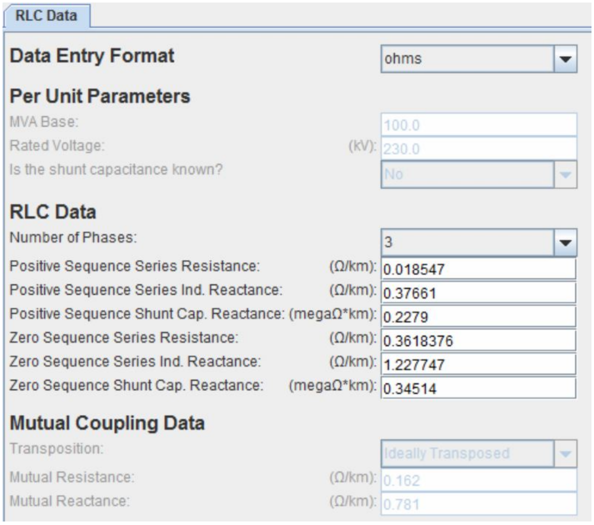
Figure 2.11: Tline Setup in RTDS

The transmission line selected for the project due to the use of multiple subsystems is the traveling wave. In order to select this type of line, some basic concepts must be taken into consideration: subsubsectionSimulation Time Step It is the time required for the system to process data[3] Based on electromagnetic waves the Propagation of the velocity is defined by the equation 2.1, and the traveling time by the equation 2.2.

$$Vp = \sqrt{\frac{1}{L*C}} \tag{2.1}$$

$$tp = \sqrt{L*C} \tag{2.2}$$

Due to system requirements citemanual, in order to handle and manage data, if traveling time in a transmission line is less than the simulation time step. Then a Pi model transmission line can be used. It must also be considered that Pi model transmission



Data Entry Format ohms

Per Unit Parameters

MVA Base: 100.0

Rated Voltage: (kV): 230.0

Is the shunt capacitance known? No

RLC Data

Number of Phases: 3

Positive Sequence Series Resistance: (Ω/km): 0.018547

Positive Sequence Series Ind. Reactance: (Ω/km): 0.37661

Positive Sequence Shunt Cap. Reactance: (megaΩ*km): 0.2279

Zero Sequence Series Resistance: (Ω/km): 0.3618376

Zero Sequence Series Ind. Reactance: (Ω/km): 1.227747

Zero Sequence Shunt Cap. Reactance: (megaΩ*km): 0.34514

Mutual Coupling Data

Transposition: Ideally Transposed

Mutual Resistance: (Ω/km): 0.162

Mutual Reactance: (Ω/km): 0.781

Figure 2.12: Electrical parameters of Tline in RTDS

lines do not allow connection between subsystems. For that reason, if it's required to use traveling waves a readjustment of the distance and the parameters of the line is compulsory.

For example, assuming a propagation velocity equal to the speed of the light and a simulation time step of 50 μ s, then, the minimum distance for a transmission line to be modelled as traveling wave is 15 Km. If it is not the case in base of that distance the capacitance and inductance of the transmission line must be recalculated. Figure 2.13 shows the algorithm used for selecting transmission line types in the RTDS.

As required for the several interconnections between subsystems, and taking into consideration that traveling waves produce less computational effort. All lines were modeled as traveling waves. Power Factory model keeps all transmission lines with a length of 1km, then all parameters of the transmission lines were recalculated as well as new distances are presented. Table 7.2 presented as a show the new values and distances of the transmission lines that were used to model in the RTDS.

CAPACITOR AND REACTOR

Capacitors and Reactors are defined by their capacitance and inductance value. This values were taken from Power Factory, and converted from MVAR to capacitance values μ F. Figure 2.14, present the menu to implement the capacitor in the RTDS.

LOADS

There are several classes of loads available in the library of the RTDS, According to the Power Factory, all loads are constant for this model. To simulate the same behavior in the RTDS, static loads were selected at the beginning of the model. Even though, if the

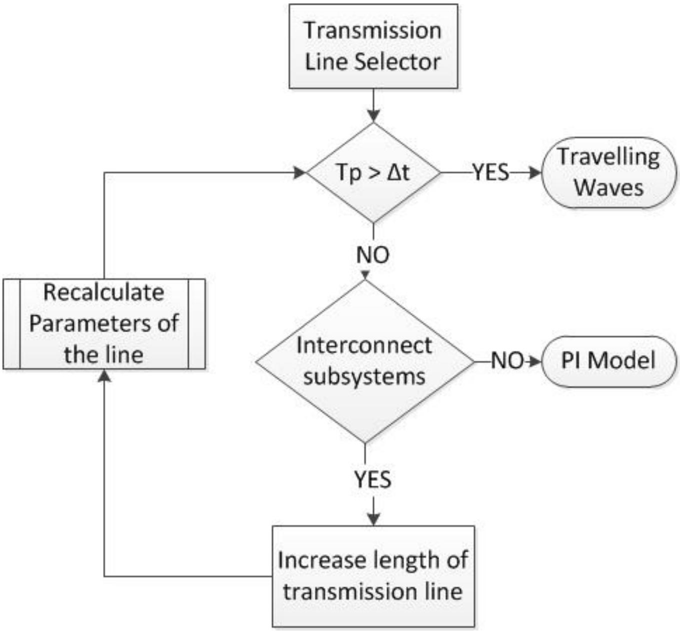
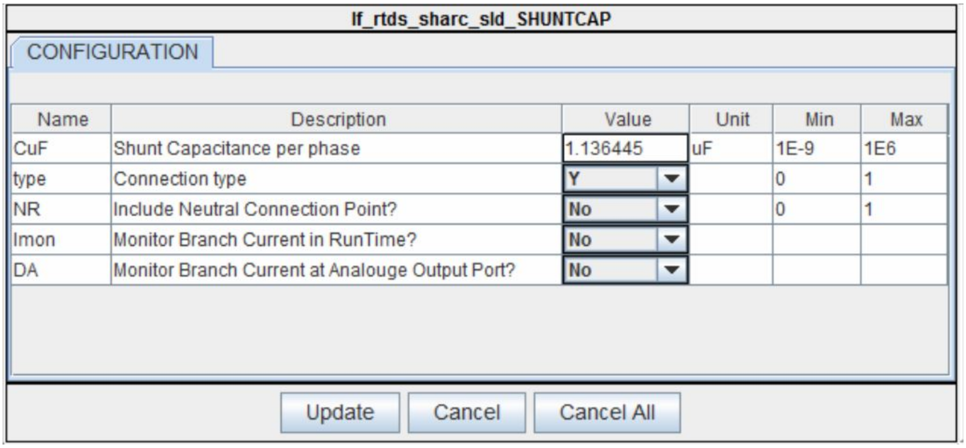


Figure 2.13: Transmission line selector process in RTDS



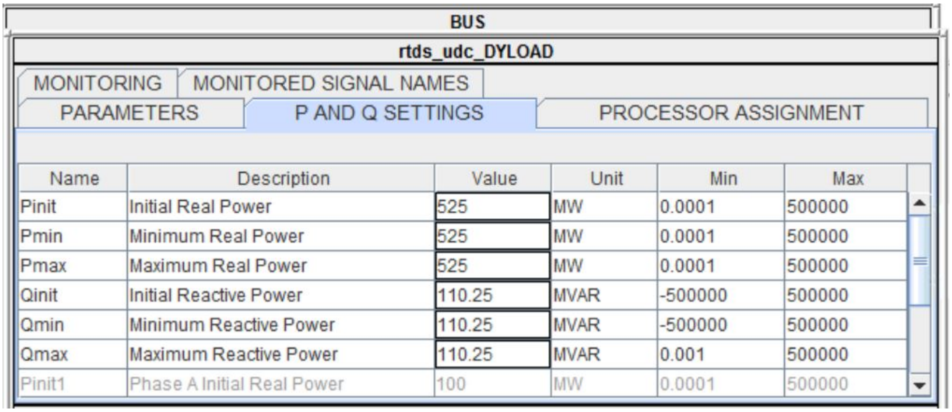
lf_rtds_sharc_sld_SHUNTCAP

CONFIGURATION

Name	Description	Value	Unit	Min	Max
CuF	Shunt Capacitance per phase	1.136445	uF	1E-9	1E6
type	Connection type	Y		0	1
NR	Include Neutral Connection Point?	No		0	1
Imon	Monitor Branch Current in RunTime?	No			
DA	Monitor Branch Current at Analouge Output Port?	No			

Figure 2.14: Shunt Capacitor in RTDS [3]

simulation involves an increase or decrease of the load, it is necessary to change manually the parameters and not from the runtime. This drawback was solved, using dynamic loads with fixed set values of active and reactive power. To give flexibility to the loads, it is set $+-50\%$ of the set value for the maximum and minimum limit of the load. If it's not required the values of the minimum and maximum limits could be the same as the initial. Figure 2.15, present the window were the parameter of the load can be modified in the RTDS.



Name	Description	Value	Unit	Min	Max
Pinit	Initial Real Power	525	MW	0.0001	500000
Pmin	Minimum Real Power	525	MW	0.0001	500000
Pmax	Maximum Real Power	525	MW	0.0001	500000
Qinit	Initial Reactive Power	110.25	MVAR	-500000	500000
Qmin	Minimum Reactive Power	110.25	MVAR	-500000	500000
Qmax	Maximum Reactive Power	110.25	MVAR	0.001	500000
Pinit1	Phase A Initial Real Power	100	MW	0.0001	500000

Figure 2.15: Dynamic Load as Constant Load in RTDS

2.3.4. LIMITATIONS

As reviewed at the beginning of the chapter, using RTDS has many advantages regarding processing and velocity that are not possible to achieve with a different kind of software, due to the physical particular hardwe equipment it handles. Nevertheless, as all of the equipment, there are limitations which dictate the way to use the system. These limitations are specified for the system used for the preparation of the document. There are two main drawbacks founded in the use of the RTDS to simulate the GB system.

- **The number of calculations must not overpass the time step specified.**

  When working with big systems, it is distributed in several subsystems. Even though there is the possibility to have as many elements and controls as it is allowed, but the system can not handle to complete the process by the end of the time step. If that is the case, then it must be considered to reduce the number of calculations with a new distribution of the elements. If it is not possible to reduce the elements, then the time step must be increased to let the system more time to handle with the calculations. It must be noticed that a new time step will affect the system if there are transmission lines modeled as traveling waves. Then the transmission lines must be recalculated as showed in the last section. In order to simulate faults the time step was increased from 50us to 60 us for simulation purposes.

- **The system can not handle an infinite number of electrical nodes**

The system can not handle an infinite number of electrical nodes. As the majority of the simulators, there are limitations in the number of elements. As presented at the beginning of the chapter, the RTDS used in the thesis is composed by six racks, each rack has the PB5 processor card which allows handling a maximum of 72 single phase nodes and 100 single phase switches. Even though it was also mentioned that the number of nodes could be doubled to 144 adding a second PB5 processor. It mus be noticed that the main drawback trying to use less quantity of racks for modeling the GB system was the processors that the RTDS can handle per card. Figure 2.16, is an example of the use of cards with the processors in a subsystem. If the number of processors is higher than the system capabilities, the use of a new subsystem is required.

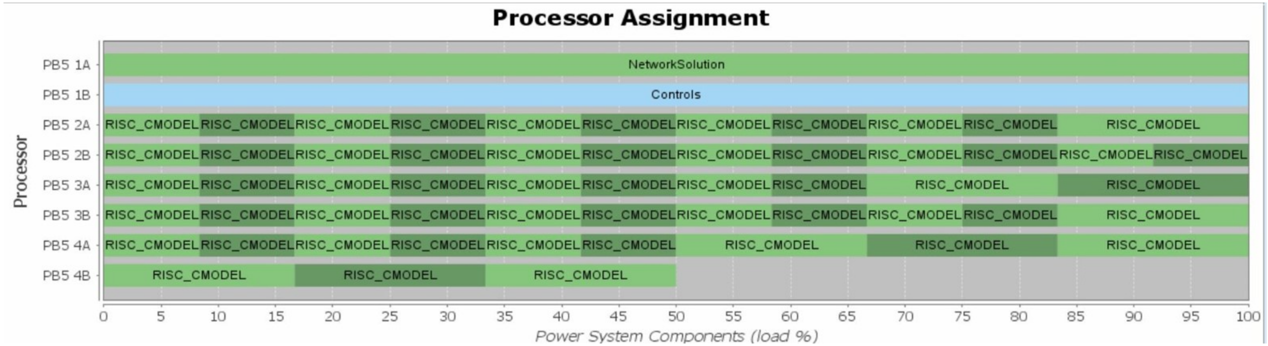


Figure 2.16: Processors behavior in the RTDS per subsystem

Due to this limitations, the version of the GB system in the RTDS uses four racks. Use this number of racks is not the best solution taking into consideration that the university has a total of 6 racks. Due to this model, a reduction of the system must be recommended if future analysis requires incorporating new elements like dynamic loads or wind generators. Next chapter will develop a coherency analysis to provide recommendations for the future use of the GB model in the RTDS.

.

2.3.5. IMPLEMENTING THE GB SYSTEM IN THE RTDS

Knowing the components available and the limitations of the RTDS. The GB model was implemented in the draft mode of the RTDS, all parameters and configurations were taken from the Power Factory model. Then the system is implemented in four subsystems (4 racks). The distribution of the zones in the RTDS system was determined as presented next:

- **Subsystem 1:** Zone 1, Zone 2, Zone 3, Zone 4, Zone 5, Zone 6, Zone 7.
- **Subsystem 2:** Zone 8, Zone 9, Zone 10, Zone 11, Zone 12, Zone 13, Zone 14, Zone 15.
- **Subsystem 3:** Zone 16, Zone 17, Zone 18, Zone 19, Zone 20, Zone 21, Zone 22, Zone 23.
- **Subsystem 4:** Zone 24, Zone 25, Zone 26, Zone 27, Zone 28, Zone 29.

The first version of the model keeps the system with visible interconnections between Zones. Four subsystems are used to implement the model. Figure 2.17 represents the first version of the GB model in the RTDS, it is notable that each of the squares represents a subsystem. Even though this version allows a fast supervision of the system; it is not practical when new elements or modifications are required in it. A new where each zone can be independent of the other allows to implement new components as well as delete or modify unnecessary ones. This new modeling design is important for a fast implementation of the rest of scenarios described for the GB system.

A final version of the system was modeled with the substitution of wind generators by synchronous generators, achieving a balance between generation and load. In this version, the zones present independent connection due to the use of traveling waves transmission lines for interconnection between zones. This version allows moving areas to another subsystem which will represent a huge advantage in future studies. Figure 2.18 presents a subsystem where the zones are separated and modeled inside each own box. Once finalized the modeling both systems must have similar behaviors. However, a parameter initialization comparison is required in order to confirm that all parameters, as well as the model, represent the GB model of the Power Factory in the RTDS.

2.3.6. INITIALIZATION COMPARISON

Figure 2.19 presents a zone modeled in power factory and the same zone modeled in RTDS. The main difference is that in power factory the generator controllers are designed

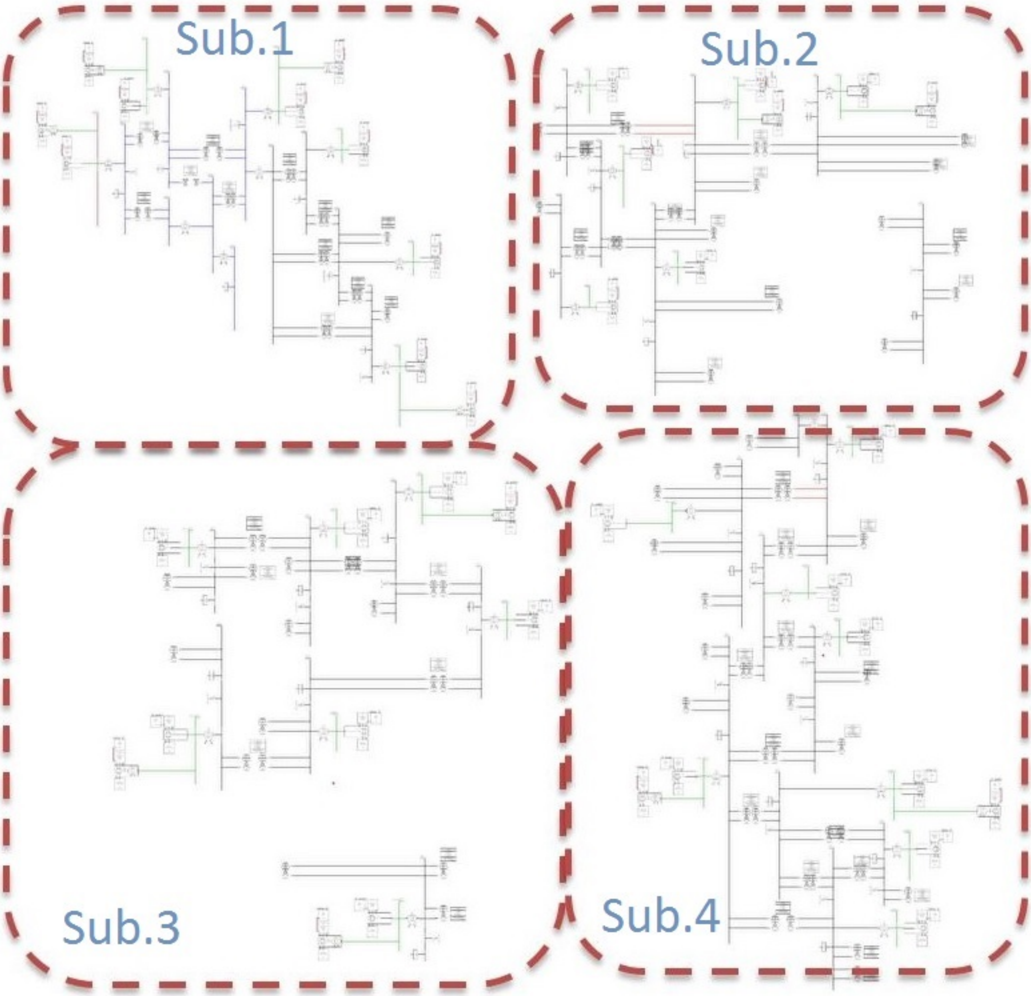


Figure 2.17: GB mounted in the RTDS

Figure 2.18: Representation of Zones in RTDS

inside the generator, while in the RTDS all controllers have a graphical representation. When all elements of the power system are modeled and interconnected. The initialization of the parameters used for each element must be tested. To evaluate the balance between generation and load, and obtain the values of voltage magnitude and voltage angle it is required to perform a power flow. RTDS and Power factory allow simulating a power flow using the same method called Newton Raphson [22]. Due to this characteristic in the RTDS it is possible to compare that initialization values are compatible with the values obtained in Power Factory.

As the model in power factory is running with no problem, it is feasible to extract the results of a power flow as a text file. This advantage is not possible at the moment in the RTDS; however, there are some files in the RTDS which make possible to compare the power flow without the necessity of review inside each of the bus bars the results of the power flow.

In order to obtain the power flow from the RTDS, two files must be taking into consideration: ".rtp file" and ".dtp file". **".rtp file"** is the file wich contains the parameters of the dynamic devices of the system modeled in RTDS, is it similar to ".raw" file used in PSS/E; both files have the same sequence. **".dtp file"** it contains the network of the modeled system, it also contains the information of the buses and generators after running a power flow.

Using the ".dtp file", it is possible to extract the voltage angle and magnitude of each bus bar of the network. A macro developed in Excel called "PowerFlow_extraction" allows extracting the information of the power system using the file which can be found in the folder where the simulation is running, or it can be exported from the draft mode to any location in the system. The macro is attached as Annex 7.1 to the project.

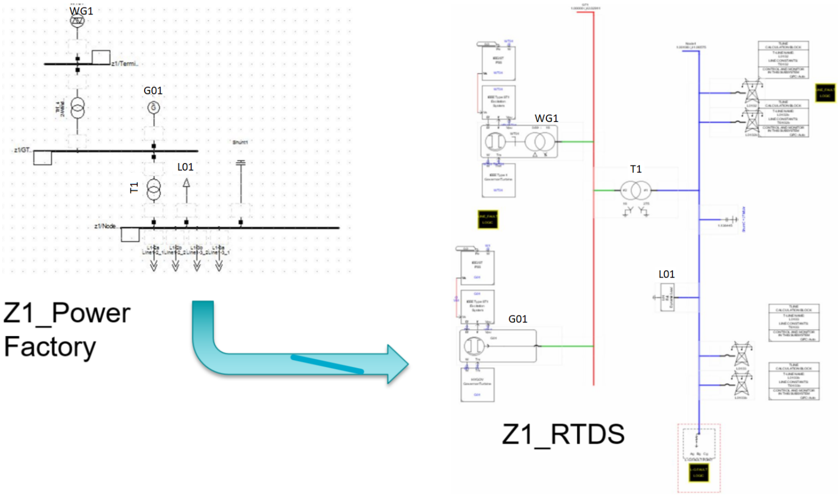


Figure 2.19: Comparison a Zone in RTDS and Power Factory

Annex 7.1, locate the bus bars in the file extracted from the RTDS, once located the bus bars it select the values of voltage angle and magnitude after the power flow is achieved. When the voltages in magnitude and angle are available from both systems, they are compared in order to demonstrate that the initialization parameters are compatible in both systems.

Figure 2.20, present the voltage magnitude in both systems when a power flow is performed in both systems. It can be noticed that the generator of the Zone 10 is the slack bus bar of the system. All magnitudes are similar with the magnitudes in Power Factory. Even though, the system in RTDS replace the wind generators by synchronous generators.

Figure 2.21, is the angle magnitudes in the bus bars of the electrical power system. It can be noticed that not only the voltages are similar in both systems, the angle magnitudes have a slight difference due to the loss in conversion of the parameters of the transmission lines. Even though the values are compatible, and the power flow does not present any major difference in both systems.

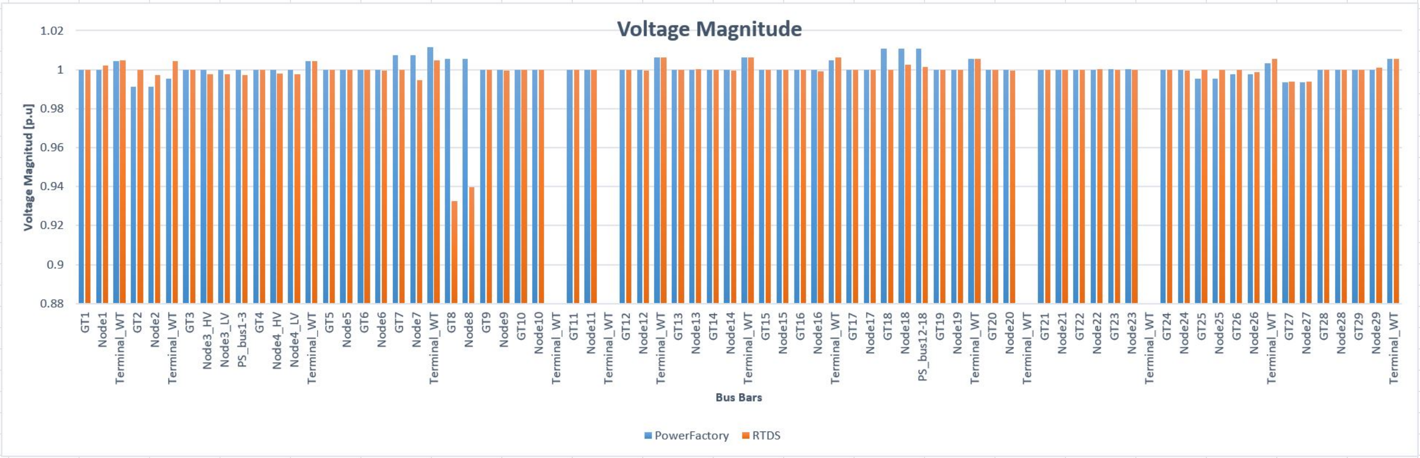


Figure 2.20: Comparison of Voltage Magnitude between systems

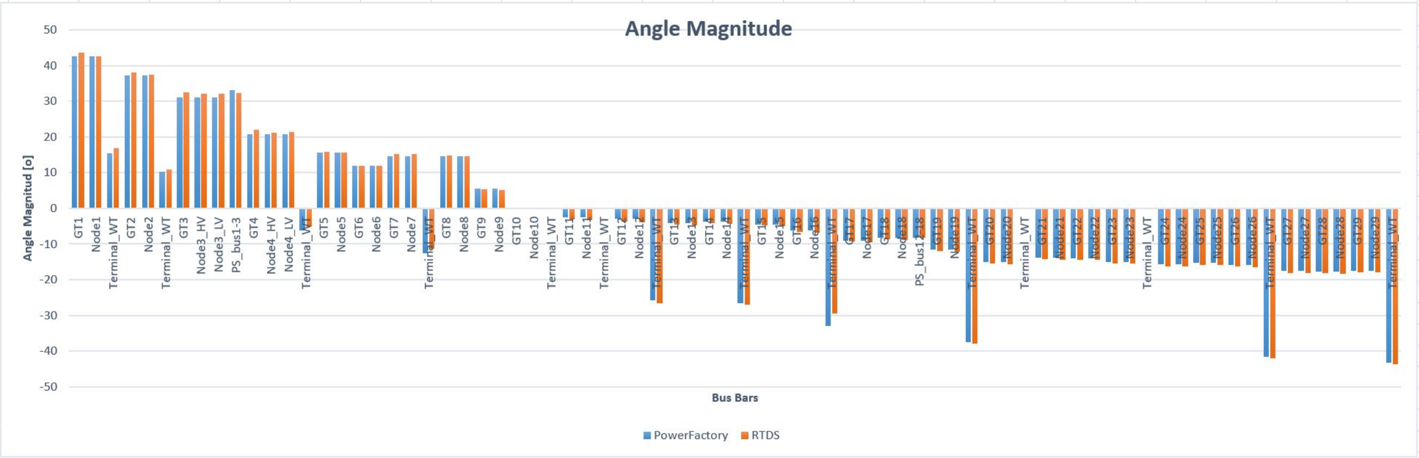


Figure 2.21: Comparison of Voltage Angle between systems

In this chapter, the GB model was presented. Additionally, the limitations of the system define the numbers of resources to use. Afterwards, the GB system was modeled in the draft mode of the RTDS, a power flow simulation was performed in order to compare the initialization results of voltage angle and magnitude with the results obtained in Power Factory. Figure 2.20 and figure2.21 present the power flow solutions for the Baseline case of the GB system. Nevertheless, due to future developments and studies involving the system, and future element integrations to the network; It is required to suggest a possibility on how to perform studies over the same model by reducing the number of racks used to simulate and evaluate the system. Next section will demonstrate the possibility of reducing the GB system in the RTDS using the time-series signals which are an output of the simulators due to the lack of Modal analysis.

Finally, as an extension of the project, Gone Green scenarios for the years 2020, 2025, 2030 and 2035 were also modeled in the draft mode of the RTDS. The gone green scenarios represent modifications not only in the dispatch of the generation and consumption of the loads but also in the replacement of the synchronous generators with wind generators in the system. All values used to model the future scenarios were taking from the table 7.4, table 7.5, table 7.6, table 7.7 for the years 2020, 2025, 2030 and 2035 respectively [4]. Gone green scenarios will also be considered in the suggestions for reducing the size of the power network due to the same limitations presented in the resources of the simulator.

3

REDUCTION OF GB SYSTEM FOR STUDY OF TRANSIENT STABILITY IN RSCAD

3.1. BACKGROUND

Once modeled the GB system in the RTDS, and due to the hardware limitations presented in the last chapter. It is required to reduce the model in order to use it for transient studies. Transient studies are focused in the fast response of the elements of a specific area when subjected to disturbances, more than the general response of the whole system. GB model contains 29 zones, using a total of four racks for the simulation in the RTDS. With the finality of using fewer components of the hardware, and focus the studies in smaller areas; A reduction of the system is presented in this chapter. Several concepts about reduction will be presented, as well as the methodology to apply it in the model.

To start with the reduction of the system, it must be taking into account that unlike Power Factory, RTDS does not offer the possibility of extracting the state matrix, or perform an eigenvalue analysis. The state matrix of the system is under development, and even though is not the topic of the chapter, it can be referred to [23] for further information. As RTDS is limited in the eigenvalue analysis, a method using information provided from the RTDS is presented. The method will make use of the time-series signals which can be extracted from RTDS. The signals will be imported to Matlab to perform a cluster analysis.

3.2. DYNAMIC COHERENCY FOR REDUCTION

The high computational effort required in order to perform transient stability analysis, derive on the focus of the study to small areas leaving the rest of the system to be considered as external areas. Under this consideration not only the computational requirements can be more relaxed, but also faster responses can be expected. The identification of the areas must be considered when a strong coupling can be detected with different elements inside the area. If there is no strong coupling between the elements, then those elements are part of different areas. Different theories and computational algorithms have been developed to identify, and aggregate elements to clusters [24]. Most of them make use of the state matrix and eigenvalue analysis. As explained RTDS does not allow such facilities to perform those mechanisms. Nevertheless, clustering time-series signals could fulfill the requirements to determine the cluster identification; furthermore, the system reduction.

3.2.1. COHERENCY ANALYSIS

In order to speed up the computation times due to specific vulnerabilities, the system will be analyzed by zones. Once selected the focusing area, this is modeled with enough detail to represent the behavior of the area. The rest of the areas connected to it are replaced by dynamic equivalents sufficient to reproduce the same influence as the originals. A general method for determining dynamic equivalents for system reduction consist of three steps [24]:

- **Cluster identification:** The first step in the reduction of electrical power systems is the identification of generators and bus bars which have a coherent behavior. There are two main groups of mechanisms based on the elements used to perform this task. The model-based coherency identification, and the measurement-base coherency identification. As mention before, the first method [10, 25] requires a knowledge of the state of the system in order to perform an eigenvalue analysis of the linearized model. The second group is based on measurements, in order to identify coherency based on signals from the system more than the state of it. Due to the lack of state matrix from the system the method selected rely on the signals which should be extracted from the system.

  The coherency identification based on time-series analysis is performed using two parameters of the system the rotor velocity and the active power magnitude at the terminals of the machine. Both parameters are extracted from the system as a response of the system when applied several contingencies. Later, with help of mathematical tools (Matlab), clustering analysis are performed in order to determine the number of clusters and elements which are part of them, based on the signals extracted from the system. The methodology used for performing the cluster analysis is presented in the next section.

- **Element aggregation:**

When identified the coherency of the system, (using the clustering analysis); an equivalent Generator and Bus Bar is placed in order to represent the behavior of the cluster it belongs. According to the topology, different clusters with different elements could be founded [26]. All results and conclusions of the analysis will be presented in the next chapter.The element aggregation of generators consists of aggregate the coherent machine group into a single equivalent machine, to next eliminate load buses from external systems. After the aggregation, the system will be reduced [9].

- **Estimation of parameters:**

  Finalized the determination of clusters, the elements which belong to each of it, and the selection of equivalent elements, the GB system will be reduced. In comparison with the 29 Zone model, the expected result will be a system where main areas can be distinguished and modeled to perform rotor angle stability studies.

3.2.2. COHERENCY ANALYSIS

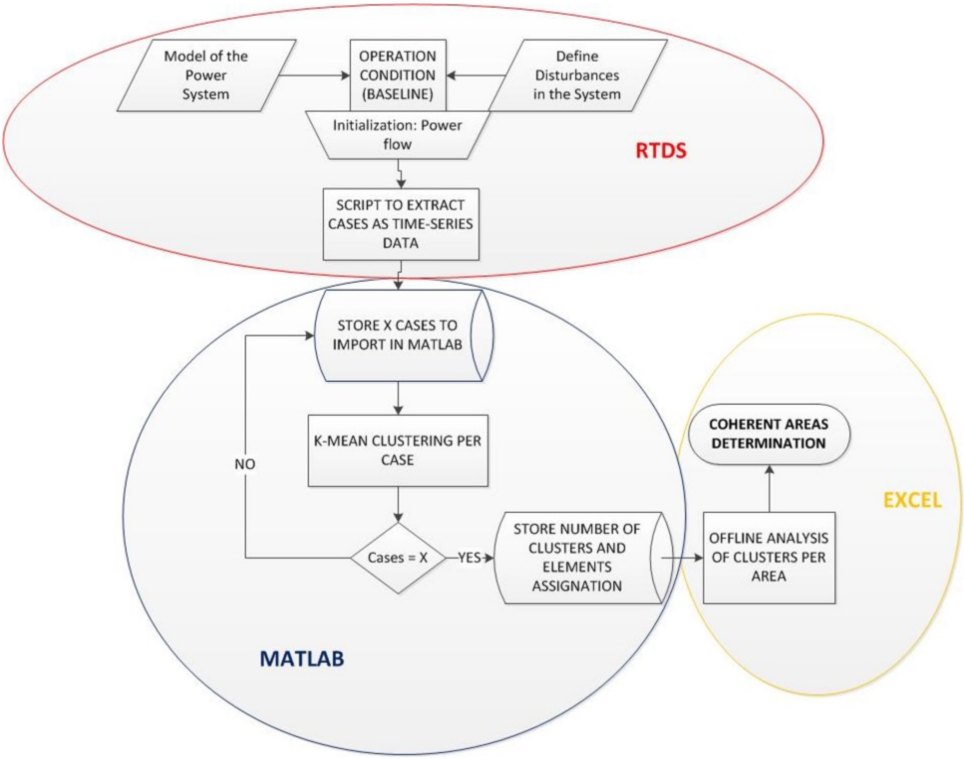


Figure 3.1: Algorithm of Coherency Analysis

Figure 3.1, present the coherency identification steps performed in the project. The first part in the RTDS the operation condition is defined taking into account the model of the system and preparing the system to run disturbances on it. After evaluating that there are no initialization problems, the scripts developed in the RunTime mode are executed.

Several scripts were prepared to extract the information from the RTDS. Most of the scripts have the same format. The variables must be initialized; next, the simulation starts. Subsequently, the disturbances are executed and finally, the signals from the plots are stored on the local machine. The simulation time for all simulations is 5s. It is considered for bus-fault contingencies, it is necessary to define the logic of the fault (presented in chapter 2) and connect the fault point in each bus bar. The faults in the buses are set to occur at the 1.25s of the simulation time with a duration of 150ms. For Line Switching, it is necessary to modify all transmission lines adding a switch to each side of the line. The logic defined will open both sides of the line at the same time. Finally, the load will be increased by 50% of the active power of each load.

SIGNALS EXTRACTION:

The first step to export signals is prepared the network for running different disturbances. Fault points are mounted in each bus of the system, as well as switches in lines and slides for modifying the loads. Later, the script is developed in RTDS in order to plot in the one graph the response of active power of each generator. And in another graph the rotor velocity of each of the generators. Both graphs reflect the response of the generators of each area when subjected to 3 phase fault in each bus-bar, line disconnection, and an increase of fifty percent in each of the loads. Once the plots are produced, it will be imported to Matlab as will be explained in the next section.

Main concepts, as well as the implementation of each algorithm, are explained bellow. It must be stressed that in order to develop a baseline case, the model of the system ready in RTDS and the disturbances conditions must be evaluated before. Figure 3.1, presents the algorithm designed to run the cluster analysis.

3.2.3. CLUSTERING IDENTIFICATION

The second part of the algorithm showed on blue in the figure 3.1, was performed in Matlab. The coherency identification uses as input the signals extracted from the RTDS in the last step. In this section not only the clustering algorithm used will be presented, but also the way of how it was performed with the baseline scenario 2016. Important concepts of the clustering determination will be reviewed next.

EUCLIDEAN DISTANCE

The Euclidean distance is a metric function; it is commonly used as a basic measure for time series similarity. Equation 3.1 represent the basic equation for calculating the distance between two points, where $a[i]$ and $b[i]$ are two distant points. When a series of sequences need to be compared, the equation 3.2 is used; where A, is the matrix containing the series of sequences, with the same length (in the project case time), and B is the signal or set of signals to compare, the result will be a matrix with the distances

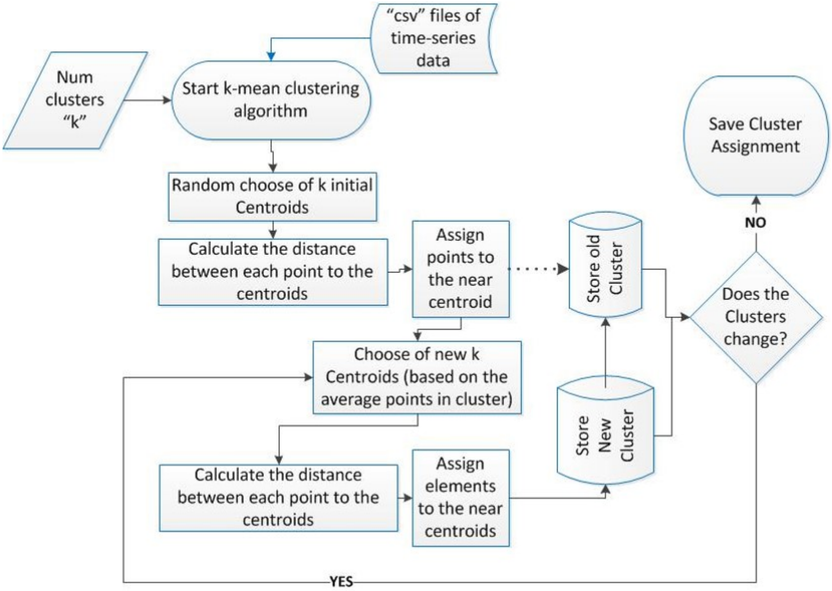


Figure 3.2: Algorithm of Clustering Identification

between the signals. Then, two signals are similar if the distance between them is less than a previously defined threshold.

$$Dist = \sqrt{\sum_{i=1}^{n}(a[i]-b[i])^2} \tag{3.1}$$

$$\|A-B\| = \sqrt{(\|A\|^2 + \|B\|^2 - 2 * A \cdot B)} \tag{3.2}$$

3.2.4. K-MEAN ALGORITHM

The k-mean algorithm allows to divide and assign the elements of a data set into groups (clusters)[27]. Additionally, the algorithm calculates the centroids of the clusters given a data set X which contain N points. To calculate the centroids in each cluster, the Euclidean distance between each point to the centroid of their cluster is determined. The equation 3.3 represent the function to minimize with respect to K clusters C_k, the distance between each point x_n and the K centroids μ_k [28].

$$min \sum_{k=1}^{K} \sum_{x_n \epsilon C_k} \|x_n - \mu_k\|^2 \tag{3.3}$$

A huge drawback for this kind of algorithm is the necessity of defining the number of clusters desired. To determine the number of clusters, the elbow method will be applied; it will be described in the next section. K-Mean algorithm uses the number of clusters and first, it define the centroids (center of a cluster), it is determined by an iterative process where the distance between signals are used, and the minimum distance to the other elements is so-called centroid. By an iterative process, each signal is compared with the other to determine the similitude between them. Once obtained the similitude between signals, those who present more similar behavior (shape) are grouped into a cluster.

In order to solve equation 3.3, it is required to use an iterative method, as the method presented by Lloyd's [28]. This algorithm converges in few steps finding a solution for a local minimum. The method as can be seen in the equations 3.4 and 3.5, consists in two steps: First, check and set centroids for each of the clusters, once the centroids μ_k have been established, the clusters are updated in function of the closest points to each centroid. Finally, with the set of clusters placed, the centroids are recalculated in order to set as the mean of all points who belong to the cluster.

$$C_k = X_n : \left\| X_n - \mu_k \right\| \leqslant all \left\| x_n - \mu_l \right\| \tag{3.4}$$

$$\mu_k = \frac{1}{C_k} \sum_{x_n \epsilon C_k} x_n \tag{3.5}$$

Figure 3.2, presents the "kmean" algorithm used for determine the number of clusters [28]. The algorithm uses the time-series signals extracted from the RTDS 7.6 as input as well as the number of clusters as discussed in the kmean algorithm. Later, the method to determine the number of clusters will be presented.

The algorithm assumes the number of clusters is known and fixed. When the input variables are determined, the first step of the algorithm starts selecting random centroids (center of the clusters) per each cluster. Using the centroids the algorithm calculates the distance between each point to the centroids. Additionally, the algorithm will aggregate the points to the closest centroid and it will store the cluster.

In the second step, a new set of centroids is calculated based on the average points inside each cluster. New distances are calculated between the points of the signal and the new centroids. The process continues normally grouping the elements to the near centroids and store the new cluster. The cluster stored from the first step is compared with the one in the second step if there are no changes in the clusters the algorithm finish running and save the final cluster. Nevertheless, if the cluster from the second step is different from the cluster in the first step, the cluster from the second step is stored and a third step is executed.

The algorithm will repeat the steps until the last cluster is equal or tolerably similar to the cluster stored in the previous step. The algorithm is performed in Matlab using the command "kmeans", it returns the assignation of the signals to the clusters, but the number of clusters must be defined at the beginning of the process. In order to obtain the number of clusters “k”, in the first instance, the same algorithm is used. The algorithm must be run several times with different values of "k".

3.2.5. ELBOW METHOD

This method is one of the oldest methods considered to find the number of clusters necessary for initialization parameters of the kmean algorithm. Elbow method is developed to find an "optimal" number of clusters based on the k-mean cluster algorithm review before [29, 30]. It uses the k-mean algorithms varying "k" to find the "optimal" or more adjuster value of "k". It is a visual method which plots the distortion in function of the number of clusters selected. At the end, the curve obtained presents the distortion which decreases when using more number of clusters. The method reviews the graph obtained and determine when an elbow is present. After that point, the distortion does not vary considerably. So the point when the curve changes from a rapid difference of distortion to a slow difference is called elbow, and the number of clusters of that point is selected for the case.

Even though, one of the drawbacks to taking into account is the computational effort as well as the time consuming for converging into a result. The results can be presented as a curve in a two-dimensional graph of number of clusters vs. variance, where the sudden change in the curve represents the "optimal" number of clusters to take. The figure 3.3 is a representation of the elbow method handle for one of the data-series of the project. As can be noticed from the figure, at some point aggregate more clusters do not represent a significant increase in the percentage of variance[29, 30]. Elbow method uses the f-test[30], which is the result of the group variance over the total variance 3.8, to plot the curve vs the number of clusters.

$$D_k = \sum_{x_i \epsilon C_k} \sum_{x_j \epsilon C_k} ||x_i - x_j||^2 = 2n_k \sum_{x_j \epsilon C_k} ||x_i - x_j||^2 \tag{3.6}$$

$$W_k = \sum_{k-1}^{K} \frac{1}{2n_k} D_k \tag{3.7}$$

Using the concept of Euclidean distance review before, it is possible to determine intra-distances between points in a cluster. Equation 3.6, represent the sum of intra-cluster distances between points inside a cluster C_k, with n_k elements. While equation 3.7, measure the compactness of the cluster using the sum of squares. W_k is the variance quantity which allows determining the optimal number of clusters.

For the implementation in Matlab, the k-means method is used from k=1 to k= total number of elements, after saving the results of all possible clusters, and using the elbow method the optimal number of clusters is determined. Then, with the "k" value discovered, the k-mean method is used getting the elements of each of the clusters. This algorithm is performed for each of the contingencies presented. The results are presented in a matrix, where the first row represents the number of clusters for that scenario, and each cell below is the element assigned to a cluster. The algorithm used in Matlab is described in 3.4.

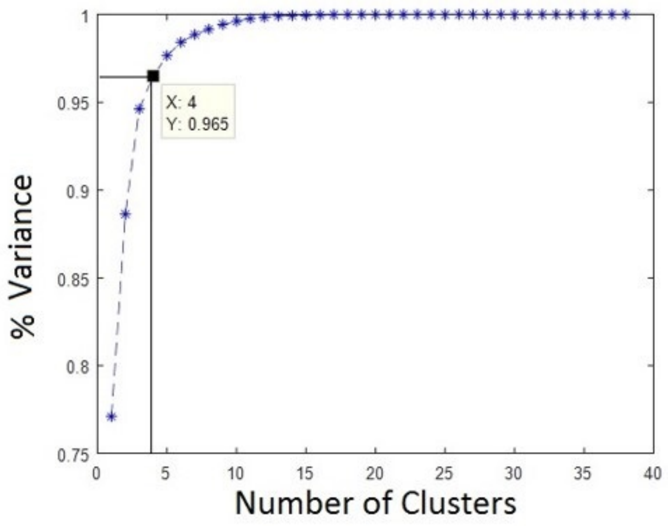


Figure 3.3: Elbow Method

$$Percentage\ of\ Variance = \frac{between\ group\ variance}{total\ variance} \tag{3.8}$$

3.3. APPLICATION OF THE COHERENCY ANALYSIS TO THE GB SYSTEM

Once reviewed the methods to perform a coherency analysis using time-series signals. It will be explained how the methods were applicated to the GB system signals.

3.3.1. DISTURBANCES IN THE RTDS

RTDS does not offer a friendly interface to simulate disturbances. In most of the cases, the model must be altered to add elements or able switches. Later the simulations can be controlled by the RunTime environment of the RTDS.

FAULT IN BUSES

A failure point and fault logic need to be connected to each bus bar in the power system model. The failure point allows determining the type of failure to simulate (1 phase, 2 phases, 3 phases and grounded or not), while the logic allows controlling the pulse du-

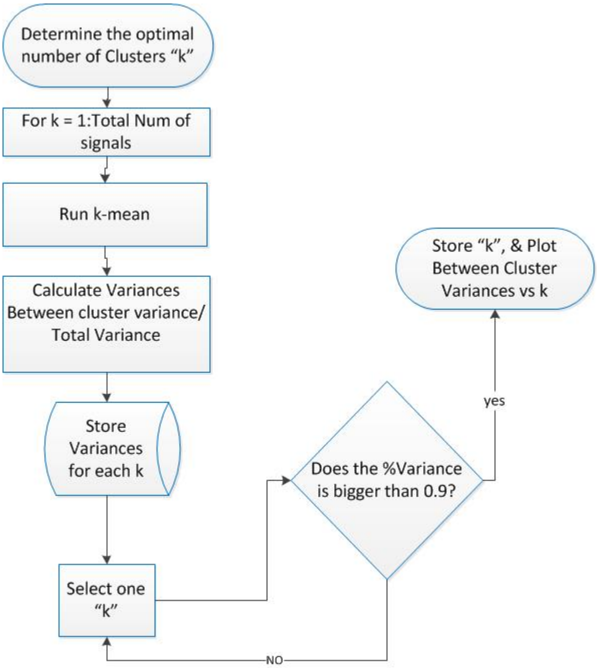
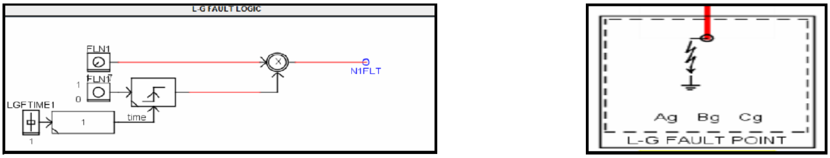


Figure 3.4: Algorithm implemented in Matlab to determine "k" by elbow method

ration and additional logics to control the disturbance. Both elements are implemented using the library and modeled in the Draft-mode of the RTDS. Figure 3.5 present the elements to simulate a three phase fault in the RTDS.



(a) Fault Logic

(b) Fault Point

Figure 3.5: Implementation of Faults in the RTDS

To all buses of the system with exception to the buses modeled as intern bus, a point of fail plus a fail logic were connected. It must be considered that each variable must have a unique name to handle the system. After connected all points, in the draft mode, the rest of the process is conducted in the RunTime mode. In RunTime mode, the signals to export must be selected and presented in a Plot.

For the project, the Active Power (P) and the rotor angle (W)were selected to analyze the behavior after disturbances. Due to, two different plots were prepared to export the active power behavior and the rotor angle when applied a 3 phase fault to each of the buses of the system. Once implemented the fault points and the logic. 3-phase faults of

100ms duration at 25% of the simulation time are set in all buses. Another benefit of the RTDS is the possibility of performing scripts to automatize the simulations. The scripts must be written in "C-language" and can control the entire RunTime environment.

Two scripts were developed to run and extract information of the RTDS system when the fault occurs in each of the buses. The script "P_busfault_Cases" and "W_busfault_Cases" are attached as an annex to the project.

The last part of the name of the scripts is "Cases," it makes reference to each time a fault is applied to a bus bar a Case is created for P and W. Each "Case" contains a set of signals for all the generators in the system. For Bus Fault in the Power System, there are 62 cases extracted; it means that a fault was applied to each of the 62 bus bars in the system. And each case is stored in a folder organized by the name assigned from case 1 to case62 for P and W, to create a database of signals for future analysis.

Annex 7.2 and annex 7.3, present the scripts which were developed in C language. Due to the extension of the script, there are just 3 cases uploaded. Even though the rest of the script is the same for the rest of buses. The script starts with the definition of variables. Then, with the command "Start" the Runtime Start the simulation of the power system. After a pause to let the system stabilize after turning it on, the first fault is applied to the fist bus bar in the system. Finally, a command to export the signals from the plot is executed and turn off the simulation. This script repeats the same actions to each of the buses for the 62 Cases. At the end two files are stores ".out" and ".mpb'. The file ".out" contain the simulation with the signals which will be processed later. The behavior of both scripts, the main difference is the output. While the first case extracts each P of the generator, the second case extract W of each one.

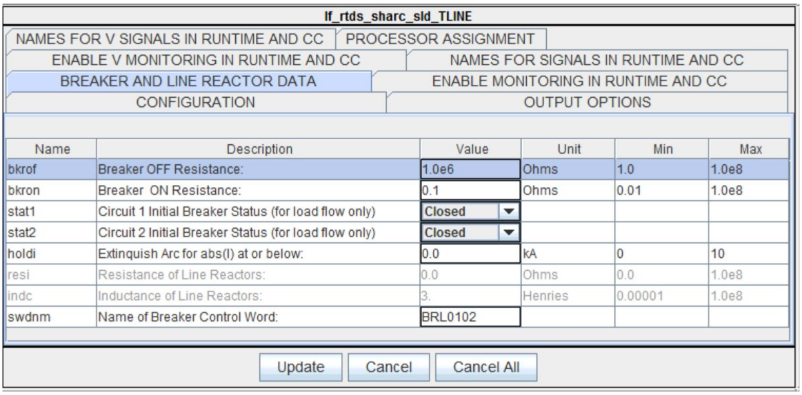
LINE SWITCHING

The procedure with this type of disturbance is similar to the bus fault, but instead of setting fault points, the switches on each side of a line must be turned on. It must be taking into consideration the limitation of the number of switches per subsystem. Even though, the signal for opening and closing the switches can be used for both sides of the transmission line. Figure 3.6, present the window where the switching will be configured. In the project, all lines were set with switches to able the opening and close. And the same signal sends the order to command both sides of the switch at the same time.

Scripts in the annex7.4 and annex 7.5 obtain the cases for P and W when a line is opened in the system. There are 101 Cases for P and Q, due to most of the lines are double circuits, and the model was changed to switch one of the circuits per time. In RTDS is not possible to model parallel lines as a simple element, so two elements were required.

LOAD VARIATION

As reviewed in the last chapter, the loads used in the RTDS are dynamic loads with a constant value of active and reactive power. The maximum and minimum limits of the



Name	Description	Value	Unit	Min	Max
bkrof	Breaker OFF Resistance:	1.0e6	Ohms	1.0	1.0e8
bkron	Breaker ON Resistance:	0.1	Ohms	0.01	1.0e8
stat1	Circuit 1 Initial Breaker Status (for load flow only)	Closed			
stat2	Circuit 2 Initial Breaker Status (for load flow only)	Closed			
holdi	Extinquish Arc for abs(I) at or below:	0.0	kA	0	10
resi	Resistance of Line Reactors:	0.0	Ohms	0.0	1.0e8
indc	Inductance of Line Reactors:	3.	Henries	0.00001	1.0e8
swdnm	Name of Breaker Control Word:	BRL0102			

Figure 3.6: Configuration of the line breaker in RTDS

loads were configured with a possibility increasing of the active and reactive power consumption in and +- 50%. Due to this condition, the disturbance selected for a load was an increase of 50% of the active power consumption. Scripts in the annex7.7, and the annex 7.9 present the structure to increase each load and collect the response of P and W in the system. There are 29 Cases, one per each load increased the value. Annex shows part of the script, even though the logic is the same for all loads.

3.3.2. COHERENCY ANALYSIS IN MATLAB

CLUSTERING IDENTIFICATION

Calculated k, which it was calculated using the elbow method, the algorithms will try to assign the elements to each of the k clusters defined by the centroids. First, initialize assigning the elements randomly to the centroids using the following algorithm, which allows improving the Lloyd's algorithm [28], according to the work developed by Arthur and Vassilvitskii [27]. One element is selected randomly from the dataset to be the first centroid (c_1). Then, calculate the distances from each element (c_j) to the first centroid selected as (c_1). The distance between an element (c_j) to the centroid m is defined as $d(x_m, c_j)$. Then, new centroid is selected also randomly from the data set with the probability determined by equation 3.9, where (c_{n1}) is the new centroid . In order to find the center j, the distances from each element to each centroid are calculated, and suddenly assigned to the closest centroid.

An iterative process involving all elements computation is executed to determine the distance between each element to the closest center, until k centroids are determined. Once calculated the distances between all elements to each of the centroids, the elements are assigned to the closest centroid. Finally, an iterative process of calculation of the average number of elements in each cluster to get k new centroids is performed. The process is repeated from the determination of the distance between elements and centroids until the cluster assignment does not change.

$$c_{n1} = \frac{d^2(x_m, c_1)}{\sum_{j=1}^{n} d^2(x_j, C_1)} \tag{3.9}$$

Figure 3.4 is a representation of the algorithm applied to determine the signals of the data-series to their corresponding cluster. As can be appreciated, the number of clusters "k" is already assumed. Nevertheless, the value of "k" is calculated and demonstrated in the next subsection.

The script uses the Euclidean distances to define the signals that can be clustered. Annex 7.8, calls one by one the cases extracted from the RTDS, then execute the algorithm of k-mean. It uses iteratively as input for "k" values from 1 to the maximum of elements to be a cluster, and then using the variance curve, it obtains the optimal k (number of clusters). After that, it executes one more time the k-mean algorithm using the optimal k founded in the last step. All elements of the case are then associated with a cluster and finally, creates a matrix where each column corresponds to a case and each row to an element evaluated. The first row is the optimal number of clusters found for the case.

4

ANALYSIS RESULTS

In the last chapter, the methodology to determine the number of clusters in the GB system was presented. For the necessity of reducing the size of the GB system to consume fewer resources of the RTDS, coherent areas were determined. The coherent areas represent the cluster assignation of the zones which are not studied to model it with the study area. Additionally, different disturbances were applied in the elements of the complete system, leading to the extraction of three variables of the generators, which represent the behavior of the system.

This chapter presents the results obtained in the previous chapters plus an analysis for the baseline case and future scenarios. In chapter 2, the GB system modeled with 29 zones [2] was implemented in the RTDS. As a result, the 29 zones were distributed in 4 subsystems. Nevertheless, it is necessary to reduce the number of subsystems (racks), to perform future analysis. Several cases will be presented to determine different ways of reduction the GB system depending on the variables to analyze and the type of contingencies simulated in the system.

There are three types of contingencies applied to the model in order to evaluate the behavior of the system. Such as faults applied in each of the bus bars of the system, switching of the transmission lines, and increasing of the active power of the loads. All these contingencies were considered in the baseline case and the scenarios. The final goal of the chapter is to determine the reduction of the GB system based in different study cases using the method explained in the last chapter. The results were obtained for each area of study, each clustering area is in function of the disturbance applied to the system, and the variable selected from the zones (voltage terminals, active power, and velocity of the rotor). The algorithm implemented in Matlab allows to run the clustering analysis in each area, the output is the number of clusters determined for the rest of the system, and the assignation of each zone to a coherent area. When considering a study area, the columns presented in the next tables represent the disturbances applied on the zones of the area selected. For the baseline case, the disturbances applied in the system were the fault in bus bars, switching of the transmission lines, and the variation of the active power of the loads. Nevertheless, for the GONE GREEN scenarios, the variation of voltage was not performed due to the necessity of creating a new model just for that disturbance. Moreover, the study was conducted only with the fault in bus bars and switching of the lines, but, the variables extracted to represent the behavior of the system are the same as in the baseline scenario.

4.1. AREAS OF STUDY

In the previous chapters, the GB system was presented as a model with 29 Zones [2]. Due to the magnitude of the model, and the limitations of the RTDS system, a reduction is required for performing transient stability studies. For analysis purposes, in this chapter three areas are selected as the focus of future studies. The areas were selected based on geographic zones. Each area has multiple zones associated as presented next:

- Scotland Zone which will be called **North Area** and it is composed of the zone 1, zone 2, zone 3, zone 4, zone 5, zone 6, zone 7 and zone 8 of the 29 zones of the GB system.
- North and West Zone which will be called **Central Area** and it is composed of zone 9, zone 10, zone 11, zone 16, zone 12, zone 13, zone14, zone 15 and zone 17, and zone 18 of the 29 zones of the GB system.
- East and South Zone which will be called **South Area** and it is composed of zone 19, zone 20, zone 21, zone 22, zone 23, zone 24, zone 25, zone 26, zone 27, zone 28 and zone 29 of the 29 zones of the GB system.

When performing future studies in one of the three geographical areas, the area selected (North, Center or South) will remain complete with all zones which are part of the area modeled, and the rest of the areas will be replaced by coherent areas determined using the methodology presented in the previous chapter.

The Geographic areas selected to perform the clustering analysis are presented in figure 4.1, where the areas in which the GB system was divided are shown in colors. The North Area is in blue, the Central Area in red, while the South Area in Yellow. . Additionally, table 7.3, included in annexes present the assignation of each bus of the system to the area for analysis. According to the table, it can be noticed that all buses are part of the subsystem defined in Chapter 2. The number of Case is the assignation developed in Chapter 3 when signals were extracted of the RTDS. After determining the areas, disturbances will be to each one to obtain coherent-areas which will allow the reduction of the system under contingencies or specific studies.

After presented how the GB system is split into three main areas for study, and obtained the results of the clustering analysis performed in the last chapter, it is necessary to analyze the results obtained in MATLAB taking into account the response of each variable in the rest of the zones when applied disturbances in the area selected. The final system could be implemented by modeling only one of the areas North, Center or South (only the study area), plus the coherent zones obtained for the rest of the areas. This reduction will allow simulating the GB system in the RTDS using fewer subsystems which will lead in less number of racks for future studies.

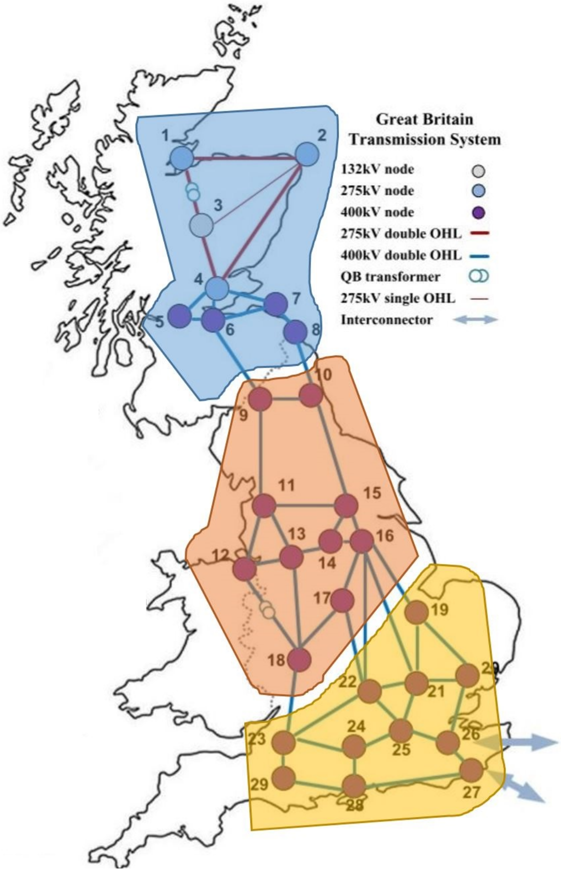


Figure 4.1: Areas of GB System

The following sections have multiple tables as outputs; all tables will be added in the annexes part of the project, meanwhile, only a few cases will be presented in order to explain the clustering applied. North Area Analysis The defined North Area of the GB system geographically belongs to Scotland. The study contemplates that several disturbances will be applied to the zones which belong to this area to obtain different coherent areas of it. The coherent areas will allow reducing the size of the system while maintaining the full model of the North Area. The method of clustering was presented in Chapter 3, even though in this section the algorithm implemented in Matlab will be reviewed.

4.2. NORTH AREA ANALYSIS

Three different classes of disturbances (bus fault, line switching, and load increasing) were defined for the analysis of the GB system. Each disturbance was evaluated in all zones of each area defined. For a first approach, the first disturbance case will be evaluated for the North Area. Similar studies can be performed for the rest of the disturbances.

Bus Faults defined in Chapter 3 were applied in the Buses of the Zone 1, Zone 2, Zone 3, Zone 4, Zone 5, Zone 6, Zone 7, and Zone 8. As the North Area would be modeled completely, in this case, the clustering analysis is performed in the rest of the GB system. Additionally, to the Bus fault, the three variables related to the generator are taken into consideration. Active power, the velocity of the rotor and the terminal voltage produce a different number of clusters as presented in the next graphs.

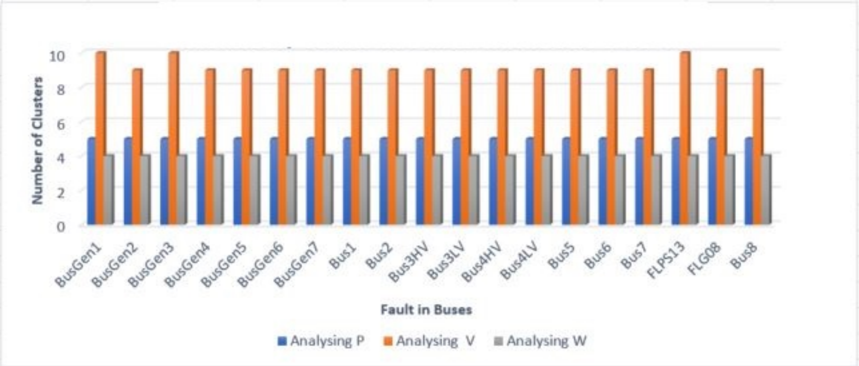


Figure 4.2: Number of Clusters determined by faults in the North Area

In the figure 4.2, the number of clusters obtained for the same disturbance are not the same. Indeed, the number of clusters depends on the parameter analyzed. For the different cases, the number of clusters varies. Moreover, the assignation of the number of clusters is different for each case. Due to that reason, it is important to develop an automatic algorithm to process the information. In each folder containing the time-series signals, it is also present the Clustering macro developed per each area of the GB system for each case. As an example, one case of cluster assignation for a disturbance in the North Area is presented.

Considering a fault in a bus in the Zone 1, the first algorithm executed in Matlab 7.10 iteratively reads the files which contain the time-series signals. In this example, the file "P_BusFault_Case_1" which belongs to the Bus Bar Fault in the Zone 1 will be analyzed. After the import of the signals and names of the elements, the number of an optimal number of clusters is calculated as presented in the last chapter. Additionally, the assignation of the signals to the clusters is executed. The result is stored in a matrix where the first row presents the names of the disturbances and the first column the elements of the system to be clustered. Each column represents a zone to which is assigned a number. This number is the cluster assignation given to it. The first column is the case to analyze, the number of clusters determined by the method cited in the last chapter is 5. It the figure 4.3, it is easy to visualize the behavior of the rest of the zones when this kind of fault occurs in the north zone.

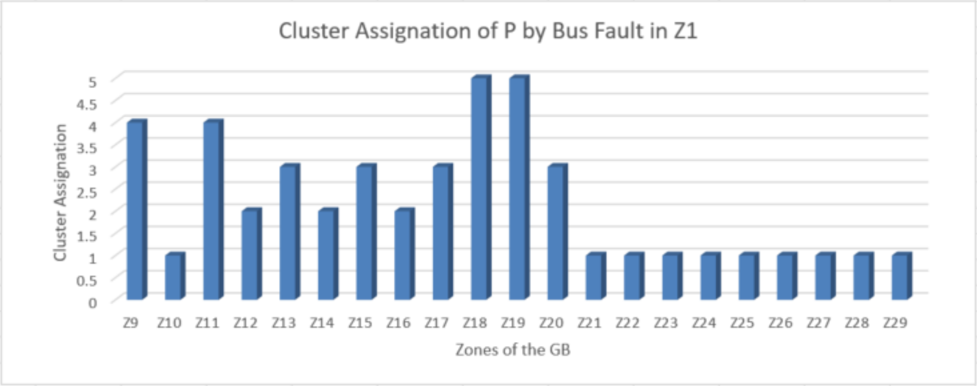


Figure 4.3: Cluster Assignation of P by Bus Fault in Z1

As the visualization of the clusters by the use of the matrix is not well convenient, an additional macro must be executed in Matlab to visualize the results in a better way. This macro allows to graphically understand the new coherent areas created in base of the methodology of the project. One of the advantages of this case is that it prints the GB system and with different colors represent the coherent behavior in the system while maintaining as constant the area of study.

In the figure 4.4, a map of the GB system with different colors in the zones appear. In black the North Area which must be modeled completely, while the rest of the zones are now part of the coherent areas. The different colors represent different clusters determined for this specific example. In the Central Area and South Area, seven clusters have been identified. This graph can be obtained for all disturbances cases set, and for the three variables chosen for analysis.

In this case, can be noticed that almost all generators in the South Area have been clustered together because they follow similar behavior when applied the fault. This coherency analysis will allow reducing the use of the subsystems and number of racks in the RTDS. According to the results presented for this particular case, the Zone North can be modeled in one Subsystem (rack), while the rest seven coherent areas can be modeled in another subsystem (rack). The coherency applied to this concrete case would reduce

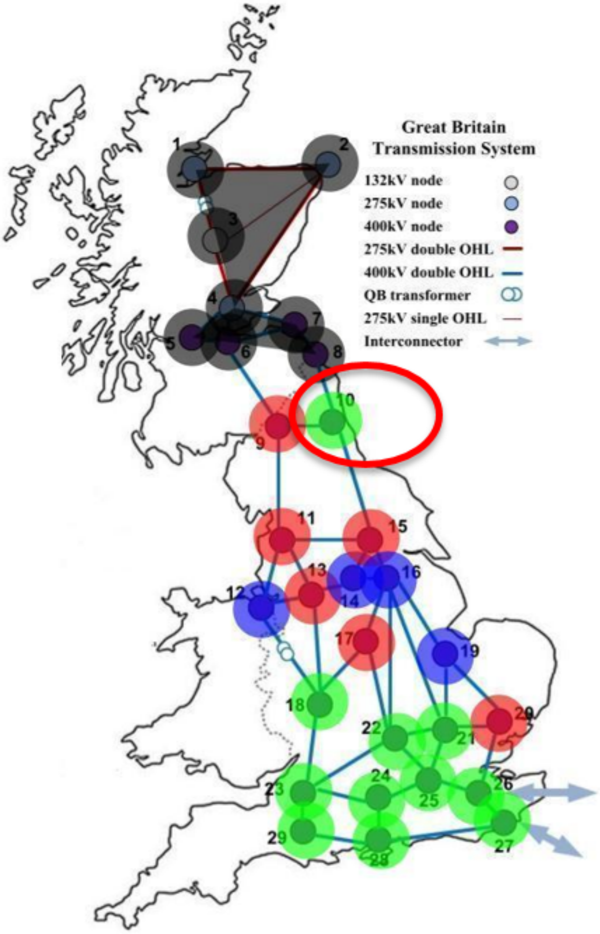


Figure 4.4: Cluster Visualization of P by Bus Fault in Z2

to 50% the consumption of the resources of the RTDS.

A similar analysis can be performed for the rest of the time-series cases obtained from the RTDS. For practical purposes, just one case will be presented for the Central Area and one for the South Area. The algorithms will be attached to the annexes of the document, as well as the matrices for the cases. For the GONE GREEN scenarios, a file containing the signals and matrices will be delivered with the project. In the figure 4.4, the clusters determined and presented. Most of the clusters are close, even though it must be noticed that the Zone 10 is set as the slack bar of the system. Due to that reason, it is not completely affected by the disturbance, and his response is similar to the remote areas.

Finally, according to the figure 4.4 three coherent areas are presented for the central and south areas in red, green and blue. Even though for future implementation three more areas also must be modeled. Let's focus on the zone 10, this area belongs to the same coherent area as the one presented at the bottom of the power system (green area). Nevertheless, the zone 10 is electrically separated from the rest of zones which are part of the green area. This result appears in all cases when the faults are performed in the North Area, and it happened because the zone 10 was established as the slack bus bar of the GB system. Taking into account that the slack bus is located in the zone 10 is it comprehensible that the behavior of the zone is similar to the farthest areas from the disturbances. A similar behavior presents the zones 12 and 20; It belongs to the coherent areas blue and red respectively. Even though, the zones do not have electrical connection with the rest of their areas. In the final reduction, both zone 12 and zone 20, as well as the zone which has the slack bus, must be modeled as independent coherent areas.

4.3. CENTRAL AREA ANALYSIS

Similarly as presented for the North Area, the Central Area is evaluated. In this case, the Central Area will be entirely modeled, while North and South Areas will be replaced by coherent areas. For Analysis of the Central Area, a fault bus in the zone 9 will be selected for evaluation. The rest of disturbances (line switching and load increasing) will be attached to the folder with the final report. The responses of the system to the fault were stored and clustered following the method explained in the last chapter. Figure 4.5, present the number of clusters obtained when taking as a focus of study the Central Area, and considering bus faults inside it.

In order to present results, the active power response when a bus fault is applied in the Zone 9 present the following clustering response. Figure **??**, represent the clusters formed in the North Area and south when a fault is applied in the zone 9 of the Central Area. Seven clusters have been determined. Indeed, according to the figure **??**, the black points represent the Central Area, the other zones present the coherent areas formed by the methodology presented in the last chapter.

According to this example, the GB system could be reduced using the full model of the central area, plus the coherent areas. This reduction allows implementing the GB model in the RTDS using two racks instead of four racks. The figure **??** was obtained using the same macro in Matlab, even though the Matlab files were split and attached to

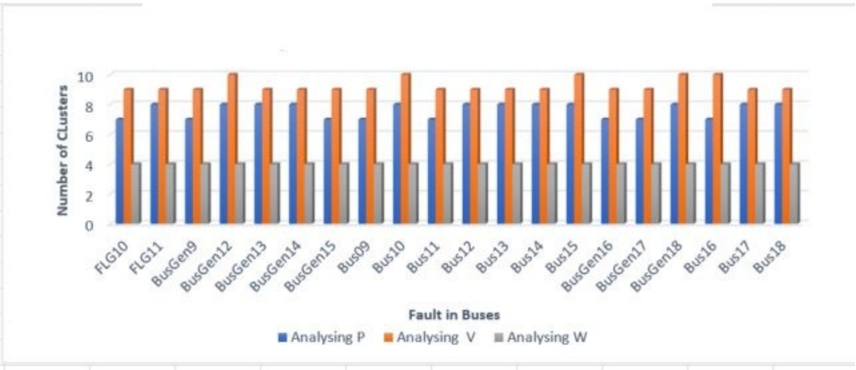


Figure 4.5: Number of Clusters of P in the Central Area

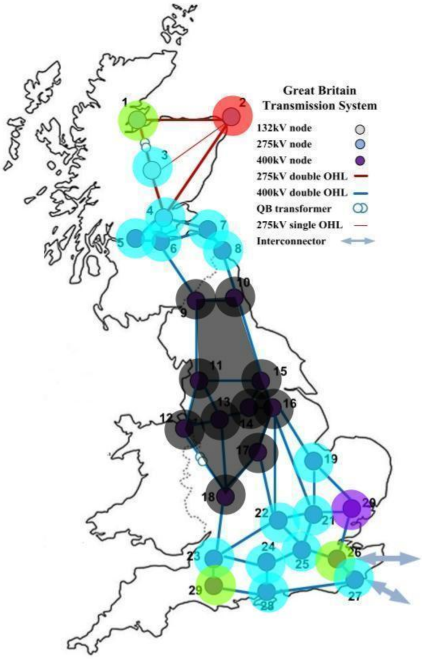


Figure 4.6: Cluster Visualization of P by Bus Fault in Z9

each type of disturbance.

4.4. SOUTH AREA ANALYSIS

The case presented for the last two areas is replicated for the South Area. Figure 4.7 represent the clusters in the GB system when a bus fault occurs in the Central Area. The fault selected for the study is a bus fault in the zone 19. In this specific case, the number of clusters is 9. The South Area will remain constant while the North and Central areas are replaced by the coherent areas.

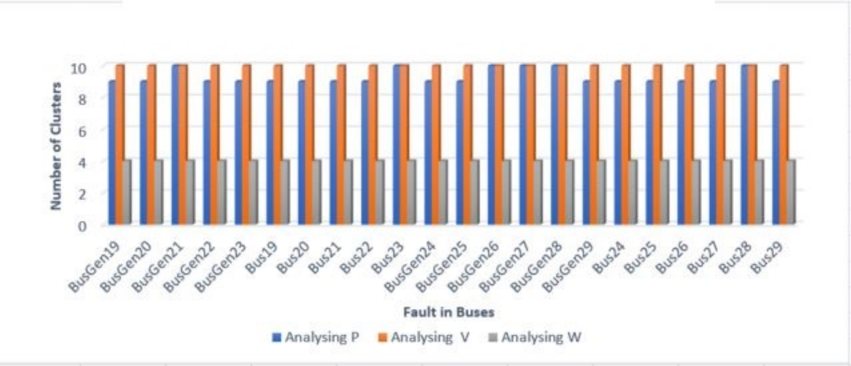


Figure 4.7: Number of Clusters of P in the South Area

The figures presenting the cluster visualization, are just a sample of the total graphs. There is a specify graph for each disturbance in each of the zones of the GB system. For the GONE GREEN scenarios, the methodology is similar taking into account that not only the dispatch is different, but also the elements connected to the buses. The graphs and the matrices used to plot it are attached to the folder of the thesis project. In the next part graphs with the differences between each disturbance in the areas are presented.

As determined by the examples presented in this chapter and according to [8], the coherency areas with the clusters depend not only on the type of disturbance but also in the location of the same. For a disturbance based only on the signals of the output parameter of the generator, the coherent areas vary. The same behavior appears for the rest of the disturbances analyzed in the thesis project. In all cases, the area of study plus the coherent areas can be easily modeled in two racks. It will allow the incorporation of new elements such as wind turbines. Finally, the algorithm developed in Matlab for the clustering analysis will allow reviewing the cluster assignation of all zones in each area of the GB model.

5

CONCLUSIONS

This is a concluding chapter which answers the main research questions as well as provides an insight about the thesis project elaborated.

As developed in the project, the GB system provided by the model in Power Factory can be modeled in the RTDS. Nevertheless, some parameters and assumptions were implemented in the RTDS such as the change of the type of transmission lines and the replacement of wind generators by synchronous generators with fixed active and reactive power. An important parameter in the RTDS is the time-step, the simulator must be capable of the process the full model during this time step. Indeed, if the time step is violated, a new time step must be adjusted and the parameters of the model such as the transmission lines must be recalculated.

In addition, the system initialization power flow results of the Power Factory can be comparable with the power flow of the RTDS for the same model, and the results are similar taking into account the assumptions applied. In Chapter 2, voltage magnitude, and voltage angle from a power flow in the Power Factory were compared with the results obtained in the RTDS. The results were positives, determining that the initial conditions for both simulators are the same. The size of the GB system as well as the limited number of RTDS racks requires the study of reduction the GB model implemented. Even though there are several possibilities to reduce the model, the use of measurement-based method was selected to perform the coherency analysis by kmean algorithm. The algorithm requires time-series signals obtained as the response of the system to disturbances.

To extract the time-series data from the RTDS, the model in the RTDS must be modified incorporating different elements such as point of faults, and breakers in the lines. This modification does not cause any affectation to the simulation, even though, if the element processing time exceeds the time-step, the system parameters must be modified. The execution of disturbances in the network is an iterative process of run the contingency and collect the information of the responses as signals. This process can be automatized by the use of scripts in the RTDS run-time environment. A k-mean clustering algorithm is a powerful tool for analyzing time-series information. The main drawback for their use in electrical power systems is that the user must know the number of clusters before performing the analysis. The elbow method uses the kmean method iteratively to determine the number of clusters.

In Chapter 4, the results of the clustering analysis were presented dividing the system into three main areas. Each area was considered as the focus area independent of the others. The results establish that while the focus area must be modeled in its entirety, the rest of the areas can be replaced by coherent areas. In most of the cases when applied the coherency analysis the model present a reduction of the 50% in the usage of the resources of the RTDS. It means that the GB system instead of using 4 racks to be modeled, it would use 2 racks. The racks which are not required can be used for future implementations in the model.

5.1. ANSWER TO RESEARCH QUESTIONS

How to ensure that power flow results and initialization obtained in power factory and RTDS are comparable? In power factory simulator, as well as in the RTDS the power flow

can be obtained via Newton Raphson. When the dispatch and model in both systems are the same, as in the two area model and later in the GB model. The power flow results can be compared. If the results of both flows are similar, it means the initialization parameters for both simulators for the model are the same. In power factory, the extraction of the power flow is implemented, and a table with the values of voltage magnitude and angle can be exported. For the RTDS, the values are presented inside each of the bus bars. In order to compare the results with the flow of the power factory an additional step to extract the flow from a system file is required.

Is there any limitation in the RTDS for implementing the GB Model? There are

two main types of limitations that can be found in the implementation of the GB model in the RTDS. The first limitation is related to the number of calculations or process in the RTDS. The processing time that the RTDS uses for the total number of calculations should not exceed the time step defined for the project. When the time step is less than the time that takes the system to process the model, an output error is presented. The easy way to deal with this inconvenient is to use more subsystems to maintain the time-step. If there is not possible to increase the number of subsystems, the time-step must be increased, even though, it means that the parameters defined for the transmission lines must be replaced. The second limitation is the limited number of electrical nodes which can be used for simulations in the RTDS. The number of nodes, as well as the number of processors, are limited in the RTDS. Due to, for large power systems, the solution to this limitation is the installation of more racks or the reduction of the systems in order to perform, specific analysis of the system.

How to reduce the GB system model in RSCAD while preserving acceptable accu-

racy? It is possible to keep the focussing area and use coherent areas to reduce the rest

of the system. At least there are 50% reduction in the use of the racks and elements.

Is it possible to perform cluster analysis based on the time-series data from the RTDS? Yes, as reviewed in the third chapter there are two main methods to perform

cluster analysis in power electrical systems. The modal-based method which uses the eigenvalue analysis, and the measurement-base method which use time-series signals to perform the cluster analysis. The method selected is part of the measurement-based method. Indeed, the solution selected is a hierarchical method called kmeans. which takes the time-series signals to determine the number of clusters and the cluster assignation. Using the kmeans algorithm in Matlab an insight about how to cluster the zones of the GB system was performed.

Thesis Main Objective:
Develop a Model of the GB system in RTDS Simulator

The GB model has been implemented in the RTDS; it includes the main component of the GB system. Wind Generators have been replaced by synchronous generators with constant active and reactive power. The model uses four racks of the RTDS to perform simulations. A coherency analysis by clustering time-series-data was performed to provide insight in the reduction of the power system.

The same analysis was performed for the GONE GREEN scenarios. These scenarios were also implemented with the same limitations and assumptions as the baseline case. The coherency analysis was extended for this scenarios. And, the models with the cluster analysis will be delivered as part of the thesis project.

5.2. FUTURE WORK

Several projects have been performed at the moment using the RTDS system. Even though, the following studies are proposed:

- Addition of wind generators considering special cases of coherency and generator aggregation and reduced network model in RSCAD. THis will allow to focus on the study of phenomena within an area of interest.
- Analysis of transient phenomena's like (voltage dip influence frequency dip) related to MIGRATE project.
- Determine the State Matrix from the "dtp" and "dta "files to perform eigenvalue analysis in RTDS.
- With the develop of dynamic loads in the RTDS, it could be incorporated to the present GB Model for future studies

6

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7

ANNEXES

7.1. ANNEX 1: SCRIPTS AND MACROS

Listing 7.1: PowerFlow_extract

```
Open folder Power_Flow
Import the dft file in excel:
    Open Excel>>Data>>From text
        Select file with the dft solution
        import in cell B1
        with separator of ":"
Create new macro:
    Open Excel>>View>>Macros>>Record>>Edit
    Copy the "Extract_PF_RTDS" text file in the macro
    Paste the macro
Run:
    Run the macro
    Voltages & Angles will be displayed
    Copy the results to a new page
Edit and Maintaining:
    Edit the macro for the internal buses created, for example:
    For the bus "WT01":
            Range("M" & Base + ix).Select
            ActiveCell.FormulaR1C1 = "WT01"
    temp1x = Cells(1 + Base, 3).Select
    tmpx = ActiveCell.Address
    Set celdax = Range("C:C").Find(What:="WT01", LookAt:=xlPart)
    Range("C" & celdax.Row + 41).Select
    'tmp2 = ActiveCell.Address
```

```
    Selection.Copy
    Range("N" & Base + ix).PasteSpecial
    Range("C" & celdax.Row + 42).Select
    Selection.Copy
    Range("O" & Base + ix).PasteSpecial
    ix = ix + 1

For the new internal buses just copy the above text and replace the
    ↪ name in red.
```

Listing 7.2: Script_P_BusFault)

```
    Writing Plot Data to an output for Matlab
           Description: Fault in different Bus Bars fixed CCT=0.15
                         Extract P
       Additional Notes: The techniques applied in this example are
           ↪ specific
       to the particular plot saved in this example. If you wish to
           ↪ use this
       script with a different plot, you will likely have to alter
           ↪ certain
       aspects of this script.
// Local Variables:
float LGFTIME,t,PG01,PG02,PG03,PG04,PG05,PG06,PG07,PWT01,PGWT2,PGWT04
    ↪ ,PWT07,PG09,PG10,PG12,PG13,PG14,PG15,PWT12,PWT14,PG16,PG17,
    ↪ PG19,PG20,PG21,PG22,PG23,PWT16,PWT19,PG24,PG25,PG26,PG27,PG28,
    ↪ PG29,PWT26,PWT29,PG08,PG11,PG18;
int i,numCases;
string datafilename,resultsfilename,dummy;
//**********
// Start the simulation
Start;
i=1;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // Apply fault
     PushButton "Subsystem #1 : CTLs : Inputs : FLGT1";
     ReleaseButton "Subsystem #1 : CTLs : Inputs : FLGT1";
    fprintf(stdmsg,"3 phase Fault on bus applied");
    // Save plot data for resulting power in generators after the
       ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
        SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Buses\
```

```
           ↪ P_BusFault_Case_"::itoa(i)::".mpb";
    datafilename = "P_BusFault_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
       ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    //Stop the simulation
Stop;
//New simulation
Start;
i=2;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // Apply Fault on Bus
    PushButton "Subsystem #1 : CTLs : Inputs : FLGT2";
    ReleaseButton "Subsystem #1 : CTLs : Inputs : FLGT2";
    ////SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102B" = 1;
    fprintf(stdmsg,"3 phase Fault on bus applied");
        // Save plot data for resulting power in generators after the
           ↪  fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
        SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Buses\
           ↪ P_BusFault_Case_"::itoa(i)::".mpb";
    datafilename = "P_BusFault_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
       ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
//Stop the simulation
Stop;
//This process will repeat for all bus bars in the model
```

Listing 7.3: W_BusFault_Cases

```
    Writing Plot Data to an output for Matlab
           Description: Fault in different Bus Bars fixed CCT=0.15
                         Extract W
```

```
       Additional Notes: The techniques applied in this example are
           ↪ specific
       to the particular plot saved in this example. If you wish to
           ↪ use this
       script with a different plot, you will likely have to alter
           ↪ certain
       aspects of this script.
// Local Variables:
float LGFTIME,t,W1,W02,W03,W04,W05,W06,W07,WT01,WT2,WT04,WT7,W9,W10,
    ↪ W11,W12,W13,W14,W15,WT12,WT14,W16,W17,W18,W19,W20,W21,W22,W23,
    ↪ WT16,WT19,W24,W25,W26,W27,W28,W29,WT26,WT29,W8,W11,W18;
int i,numCases;
string datafilename,resultsfilename,dummy;
// Start the simulation
Start;
i=1;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // Apply fault
     PushButton "Subsystem #1 : CTLs : Inputs : FLGT1";
     ReleaseButton "Subsystem #1 : CTLs : Inputs : FLGT1";
    fprintf(stdmsg,"3 phase Fault on bus applied");
    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
        ↪ Node Voltages"
    SavePlot "Rotor_speed","C:\RTDS_USER\fileman\GB_60us\Buses\
        ↪ W_BusFault_Case_"::itoa(i)::".mpb";
    datafilename = "W_BusFault_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy);
    //Stop the simulation
Stop;
//New simulation
Start;
i=2;
```

```
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // Apply Fault on Bus
    PushButton "Subsystem #1 : CTLs : Inputs : FLGT2";
    ReleaseButton "Subsystem #1 : CTLs : Inputs : FLGT2";
    ////SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102B" = 1;
    fprintf(stdmsg,"3 phase Fault on bus applied");

    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
        ↪ Node Voltages"
    SavePlot "Rotor_speed","C:\RTDS_USER\fileman\GB_60us\Buses\
        ↪ W_BusFault_Case_"::itoa(i)::".mpb";
    datafilename = "W_BusFault_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy);
//Stop the simulation
Stop;
//This process will repeat for all bus bars in the model
```

Listing 7.4: Script_Switching_Lines_P_Cases

```
    Writing Plot Data to an Excel File Script Example
    Script Developed By: Fabricio Velez
                 Date: 2017
           Description: Switching Lines
                        Extract P
       Additional Notes: The techniques applied in this example are
           ↪ specific
       to the particular plot saved in this example. If you wish to
           ↪ use this
       script with a different plot, you will likely have to alter
           ↪ certain
       aspects of this script.
// Local Variables:
```

```
float LGFTIME,t,PG01,PG02,PG03,PG04,PG05,PG06,PG07,PWT01,PGWT2,PGWT04
    ↪ ,PWT07,PG09,PG10,PG12,PG13,PG14,PG15,PWT12,PWT14,PG16,PG17,
    ↪ PG19,PG20,PG21,PG22,PG23,PWT16,PWT19,PG24,PG25,PG26,PG27,PG28,
    ↪ PG29,PWT26,PWT29,PG8,PG11,PG18;
int i,numCases;
string datafilename,resultsfilename,dummy;
// Start the simulation
Start;
i=1;
    // Wait for the system to stabilize
    Wait 3.0;
    fprintf(stdmsg,"Case Number %d\n",i);
    SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102" = 1;
    fprintf(stdmsg,"Open T/L");
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Buses\
        ↪ P_LineOut_Case_"::itoa(i)::".mpb";
    datafilename = "P_LineOut_Case_"::itoa(i)::".out";

    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102" = 0;
//Stop the simulation
Stop;
//New simulation
Start;
i=2;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
        SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102B" = 1;
    fprintf(stdmsg,"Open T/L");
    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
        ↪ Node Voltages"
    SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Buses\
        ↪ P_LineOut_Case_"::itoa(i)::".mpb";
    datafilename = "P_LineOut_Case_"::itoa(i)::".out";
```

```
        // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);

    SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102B" = 0;
//Stop the simulation
Stop;
//This process will repeat for all transmission lines defined in the
    ↪ model
```

Listing 7.5: Script_Switching_Lines_W_Cases

```


    Writing Plot Data to an Excel File Script Example
    Script Developed By: Fabricio Velez
                 Date: 2017
           Description: Switching Lines
                          Extract W
       Additional Notes: The techniques applied in this example are
           ↪ specific
       to the particular plot saved in this example. If you wish to
           ↪ use this
       script with a different plot, you will likely have to alter
           ↪ certain
       aspects of this script.
// Local Variables:
float LGFTIME,t,W1,W02,W03,W04,W05,W06,W07,WT01,WT2,WT04,WT7,W9,W10,
    ↪ W12,W13,W14,W15,WT12,WT14,W16,W17,W19,W20,W21,W22,W23,WT16,
    ↪ WT19,W24,W25,W26,W27,W28,W29,WT26,WT29,W8,W11,W18;
int i,numCases;
string datafilename,resultsfilename,dummy;
// Start the simulation
Start;
i=1;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);

    SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102" = 1;  Wait
```

```
       ↪ 30.0;

    fprintf(stdmsg,"Open T/L");
    // Save plot data for resulting power in generators after the
       ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
       ↪ Node Voltages"
    SavePlot "Rotor_speed","C:\RTDS_USER\fileman\GB_60us\Buses\
       ↪ W_LineOut_Case_"::itoa(i)::".mpb";
    datafilename = "W_LineOut_Case_"::itoa(i)::".out";
    //resultsfilename = "CaseNum"::itoa(i)::"W.csv";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
       ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
       ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102" = 0;
//Stop the simulation
Stop;
//New simulation
Start;
i=2;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);

    SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102B" = 1;
    Wait 30.0;
    fprintf(stdmsg,"Open T/L");
    // Save plot data for resulting power in generators after the
       ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
       ↪ Node Voltages"
    SavePlot "Rotor_speed","C:\RTDS_USER\fileman\GB_60us\Buses\
       ↪ W_LineOut_Case_"::itoa(i)::".mpb";
    datafilename = "W_LineOut_Case_"::itoa(i)::".out";
    //resultsfilename = "CaseNum"::itoa(i)::"W.csv";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
       ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
```

```
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0102B" = 0;
//Stop the simulation
Stop;
//This process will repeat for all transmission lines defined in the
    ↪ model
```

Listing 7.6: Script_to_csv

```
    Writing Plot Data to an output for excel Excel File
       Additional Notes: The techniques applied in this example are
           ↪ specific
       to the particular plot saved in this example. If you wish to
           ↪ use this
       script with a different plot, you will likely have to alter
           ↪ certain
       aspects of this script.
// Local Variables:
float LGFTIME,t,PG01,PG02,PG03,PG04,PG05,PG06,PG07,PG09,PG10,PG12,
    ↪ PG13,PG14,PG15,PG16,PG17,PG19,PG20,PG21,PG22,PG23,PG24,PG25,
    ↪ PG26,PG27,PG28,PG29,PG08,PG11,PG18,W1,W02,W03,W04,W05,W06,W07,
    ↪ W9,W10,W12,W13,W14,W15,W16,W17,W19,W20,W21,W22,W23,WW24,W25,
    ↪ W26,W27,W28,W29,W8,W11,W18,Nod13a,N13,N21a,Ngt21a,N131,N3hv1,
    ↪ N16,Ngt3a,N4hv1,N4lv1,Ngt4a,N5hv1,Ngt5a,N6hv1,Ngt6a,N7hv1,
    ↪ Ngt7a,N8hv1,Ngt8a,N9hv1,Ngt9a,N10hv1,Ngt10a,N11hv1,Ngt11a,
    ↪ N12hv1,Ngt12a,N13hv1,Ngt13a,N14hv1,Ngt14a,N15hv1,Ngt15a,N16hv1
    ↪ ,Ngt16a,N17hv1,Ngt17a,Np12hv1,N18hv1,Ngt18a,N19hv1,Ngt19a,
    ↪ N20hv1,Ngt20a,N21hv1,Ngt21a,N22hv1,Ngt22a,N23hv1,Ngt23a,N24hv1
    ↪ ,Ngt24a,N25hv1,Ngt25a,N26hv1,Ngt26a,N27hv1,Ngt27a,N28hv1,
    ↪ Ngt28a,N29hv1,Ngt29a;
int i,numCases;
string datafilename,resultsfilename,dummy;
// Initialization:
//PWT01,PGWT2,PGWT04,PWT07,PWT12,PWT14,PWT16,PWT19,PWT26,PWT29,
 Start;
i=2;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // Apply Fault on Bus
    PushButton "Subsystem #1 : CTLs : Inputs : FLGT2";
```

```
    ReleaseButton "Subsystem #1 : CTLs : Inputs : FLGT2";
    ////SetSwitch "Subsystem #1 : CTLs : Inputs : BRL0204B" = 1;
    fprintf(stdmsg,"3 phase Fault on bus applied");

    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    SavePlot "Pot_Act","D:\OneDrive\Thesis_TUDelft\NewNSignls\
        ↪ SCENARIO\2035\P_BusFault_Case_"::itoa(i)::".mpb";
    datafilename = "P_BusFault_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    //fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy);
    Stop;
```

Listing 7.7: Script_Load_Variation_P_Cases

```
    Writing Plot Data to an output for excel Excel File

    Script Developed By: Fabricio Velez
                   Date: 2017
               Revised: N/A
          Description: Load Increase in 50\%
                              Extraction P
       Additional Notes: The techniques applied in this example are
           ↪ specific
       to the particular plot saved in this example. If you wish to
           ↪ use this
       script with a different plot, you will likely have to alter
           ↪ certain
       aspects of this script.
// Local Variables:
float LGFTIME,t,PG01,PG02,PG03,PG04,PG05,PG06,PG07,PWT01,PGWT2,PGWT04
     ↪ ,PWT07,PG09,PG10,PG12,PG13,PG14,PG15,PWT12,PWT14,PG16,PG17,
     ↪ PG19,PG20,PG21,PG22,PG23,PWT16,PWT19,PG24,PG25,PG26,PG27,PG28,
     ↪ PG29,PWT26,PWT29,PG8,PG11,PG18;
int i,numCases;
string datafilename,resultsfilename,dummy;
// Start the simulation
Start;
i=1;
```

```
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // // Increase Load 50%
    SetSlider "Subsystem #1 : Loads : L01 : Pset" = 787.5;
     //ReleaseButton "Subsystem #1 : CTLs : Inputs : 787.5";
    fprintf(stdmsg,"Increase 50% of Load");
    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
        SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Loads\
            ↪ P_Load_Case_"::itoa(i)::".mpb";
    datafilename = "P_Load_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    //Stop the simulation
    SetSlider "Subsystem #1 : Loads : L01 : Pset" = 525;
Stop;
//New simulation
Start;
i=2;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // // Increase Load 50%
        SetSlider "Subsystem #1 : Loads : L02 : Pset" = 787.5;
     //ReleaseButton "Subsystem #1 : CTLs : Inputs : 787.5";
    fprintf(stdmsg,"Increase 50% of Load");
    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
        ↪ Node Voltages"
    SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Loads\
        ↪ P_Load_Case_"::itoa(i)::".mpb";
    datafilename = "P_Load_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
```

7

```
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    //Stop the simulation
    SetSlider "Subsystem #1 : Loads : L02 : Pset" = 525;
Stop;
//This process will repeat for all loads defined in the model
```

Listing 7.8: Script_to_csv

```

clear
clc
%FinHead contain the names of the disturbances of the network.
FinHead={'Fault in BusGen1','Fault in BusGen2','Fault in BusGen3','
    ↪ Fault in BusGen4','Fault in BusGen5','Fault in BusGen6','Fault
    ↪  in BusGen7','Fault in Bus1','Fault in Bus2','Fault in Bus3HV'
    ↪ ,'Fault in Bus3LV','Fault in Bus4HV','Fault in Bus4LV','Fault
    ↪ in Bus5','Fault in Bus6','Fault in Bus7','Fault in FLPS13','
    ↪ Fault in FLG08','Fault in FLG10','Fault in FLG11','Fault in
    ↪ BusGen9','Fault in BusGen12','Fault in BusGen13','Fault in
    ↪ BusGen14','Fault in BusGen15','Fault in Bus8','Fault in Bus09'
    ↪ ,'Fault in Bus10','Fault in Bus11','Fault in Bus12','Fault in
    ↪ Bus13','Fault in Bus14','Fault in Bus15','Fault in BusGen16','
    ↪ Fault in BusGen17','Fault in BusGen18','Fault in BusGen19','
    ↪ Fault in BusGen20','Fault in BusGen21','Fault in BusGen22','
    ↪ Fault in BusGen23','Fault in Bus16','Fault in Bus17','Fault in
    ↪  Bus18','Fault in Bus19','Fault in Bus20','Fault in Bus21','
    ↪ Fault in Bus22','Fault in Bus23','Fault in FLPSB1218','Fault
    ↪ in BusGen24','Fault in BusGen25','Fault in BusGen26','Fault in
    ↪  BusGen27','Fault in BusGen28','Fault in BusGen29','Fault in
    ↪ Bus24','Fault in Bus25','Fault in Bus26','Fault in Bus27','
    ↪ Fault in Bus28','Fault in Bus29'};
% Then a pop-up window will ask for the zone to perform the analysis
    ↪ (North, Central or South)
AreaSel=menu('Select an Area to Perform the Study','Area North','Area
    ↪  Central','Area South','ALL');
Ars = AreaSel-1;
% Area North selected
if Ars == 0
%OptK and Assig: determine the final matrix output containing the
    ↪ number of clusters and the cluster assignation for each case.
    OptK=zeros(1,62);
```

```
    Assig=zeros(21,62);
% for loop for read each case depending of the area of study
for i = 1:18
    %import the case to open
   AAX = sprintf('P_BusFault_Case_%d.out', i);
   AAi=importdata(AAX,' ');
   AAx1=AAi.data;
   %The next section will modify the file to make it easy to work on
       ↪ it
       AA=AAx1(:,10:size(AAx1,2));
     % A=readtable(AA.data);
     %%%select the correct heads for the data%%%
       heady=strsplit(AAi.textdata{1},' ');
       heady2=heady(1, 2:2:end);
       head1 = strrep(heady2,'#1|Machines|','');
       head2 = strrep(head1,'#2|Machines|','');
       head3 = strrep(head2,'#3|Machines|','');
       head4 = strrep(head3,'#4|Machines|','');
       headx1 = strrep(head4,'"','');
       head = headx1(1, 10:size(headx1,2));
       %delete some variables not used anymore
      clearvars head1 head2 head3 head4 heady heady2
      %select signals already imported
       element=size(AA,2);
       x = AAi.data(:,1);
       y=AA(:,1:element);
       %normalize the signals
       yy = bsxfun(@times, bsxfun(@minus,y,min(y)), 1./range(y));
       Aedit=[x yy];
       % modify the output signals
       A1=transpose(Aedit);
       a1=size(A1,1);
       A2=A1(2:a1,:);
%Calculate the distance, (it can be omitted)
       Dist = pdist(A2,'euclidean');
%Calculate hierarchical clusters of the rows of the data based on the
%Euclidean distance (it can be omitted)
       Z=linkage(A2);
        Tic %start measuring time
%call the function opt_kmeans to find the optimal number of clusters
       [IDX,C,SUMD,K]=opt_kmeans(A2);
%populate final matrix with the results of k and assignation of
    ↪ clusters
       Assig(:,i)=IDX;
       OptK(:,i)=K;
```

```
        Toc %stop measuring time
%plot of the signals and save it (it can be omitted)
plot(x,yy(:,1), x,yy(:,2), x,yy(:,3),x,yy(:,4),x,yy(:,5),x,yy(:,6),x,
    ↪ yy(:,7),x,yy(:,8),x,yy(:,9),x,yy(:,10),x,yy(:,11),x,yy(:,12),x
    ↪ ,yy(:,13),x,yy(:,14),x,yy(:,15),x,yy(:,16),x,yy(:,17),x,yy
    ↪ (:,18),x,yy(:,19),x,yy(:,20),x,yy(:,21))
legend(head);
saveas(1,sprintf('P_BusFault_North_%d.png',i))
i %go to the next case
end
%prepare the output file
Fin1=[OptK;Assig];
Fin2=[Fin1(:,1:18) Fin1(:,26)];
headtr=transpose(head);
headtr=['K';headtr];
Fin3=num2cell(Fin2);
Fin4=[headtr Fin3];
%add the titel row to the output
NameUp=['K' FinHead(1:18) FinHead(1,26)];
%Fin is the final output
Fin=[NameUp;Fin4];
 %save the final matrix in excel format and MATLAB format
  save('P_BusFault_North.mat','Fin');
 filename = 'P_BusFault_North.xlsx';
xlswrite(filename,Fin);
```

Listing 7.9: Script_Load_Variation_W_Cases

```
    Writing Plot Data to an output for excel Excel File
    Script Developed By: Fabricio Velez
                   Date: 2017
                Revised: N/A
            Description: Load Increase 50%
                            Extraction W
    Additional Notes: The techniques applied in this example are
        ↪ specific
       to the particular plot saved in this example. If you wish to
           ↪ use this
       script with a different plot, you will likely have to alter
           ↪ certain
       aspects of this script.
// Local Variables:
float LGFTIME,t,W1,W02,W03,W04,W05,W06,W7,WT01,WT2,WT04,WT7,W9,W10,
    ↪ W12,W13,W14,W15,WT12,WT14,W16,W17,W19,W20,W21,W22,W23,WT16,
    ↪ WT19,W24,W25,W26,W27,W28,W29,WT26,WT29,W8,W11,W18;
```

```
int i,numCases;
string datafilename,resultsfilename,dummy;
// Start the simulation
Start;
i=1;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // // Increase Load 50%
    SetSlider "Subsystem #1 : Loads : L01 : Pset" = 787.5;
     //ReleaseButton "Subsystem #1 : CTLs : Inputs : 787.5";
    fprintf(stdmsg,"Increase 50% of Load");
    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
        ↪ Node Voltages"
    SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Loads\
        ↪ W_Load_Case_"::itoa(i)::".mpb";
    datafilename = "W_Load_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    //Stop the simulation
    SetSlider "Subsystem #1 : Loads : L01 : Pset" = 525;
Stop;
//New simulation
Start;
i=2;
    // Wait for the system to stabilize
    Wait 3.0;
    // Print case number in the "Message Area" of Runtime
    fprintf(stdmsg,"Case Number %d\n",i);
    // // Increase Load 50%
    SetSlider "Subsystem #1 : Loads : L02 : Pset" = 787.5;
     //ReleaseButton "Subsystem #1 : CTLs : Inputs : 787.5";
    fprintf(stdmsg,"Increase 50% of Load");
    // Save plot data for resulting power in generators after the
        ↪ fault
    fprintf(stdmsg,"Saving plot data for Case Number %d\n",i);
```

```
    //ojo en la siguiente linea con el nombre del plot "Subsystem #1|
        ↪ Node Voltages"
    SavePlot "Pot_Act","C:\RTDS_USER\fileman\GB_60us\Loads\
        ↪ W_Load_Case_"::itoa(i)::".mpb";
    datafilename = "W_Load_Case_"::itoa(i)::".out";
    // Skip the header before parsing
    fscanf(datafilename,"%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
        ↪ %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s",dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,dummy,
        ↪ dummy,dummy,dummy,dummy,dummy,dummy,dummy);
    //Stop the simulation
    SetSlider "Subsystem #1 : Loads : L02 : Pset" = 525;
Stop;
```

Listing 7.10: Clust_P_BF_ZN

```
clear
clc
%Head final
FinHead={'Fault in BusGen1','Fault in BusGen2','Fault in BusGen3','
    ↪ Fault in BusGen4',
'Fault in BusGen5','Fault in BusGen6','Fault in BusGen7','Fault in
    ↪ Bus1','Fault in
Bus2','Fault in Bus3HV','Fault in Bus3LV','Fault in Bus4HV','Fault in
    ↪  Bus4LV','Fault
in Bus5','Fault in Bus6','Fault in Bus7','Fault in FLPS13','Fault in
    ↪ FLG08','Fault
in FLG10','Fault in FLG11','Fault in BusGen9','Fault in BusGen12','
    ↪ Fault in BusGen13'
,'Fault in BusGen14','Fault in BusGen15','Fault in Bus8','Fault in
    ↪ Bus09','Fault in
Bus10','Fault in Bus11','Fault in Bus12','Fault in Bus13','Fault in
    ↪ Bus14','Fault in
Bus15','Fault in BusGen16','Fault in BusGen17','Fault in BusGen18','
    ↪ Fault in Bus
Gen19','Fault in BusGen20','Fault in BusGen21','Fault in BusGen22','
    ↪ Fault in Bus
Gen23','Fault in Bus16','Fault in Bus17','Fault in Bus18','Fault in
    ↪ Bus19','Fault in Bus20',
'Fault in Bus21','Fault in Bus22','Fault in Bus23','Fault in
    ↪ FLPSB1218','Fault in
BusGen24','Fault in BusGen25','Fault in BusGen26','Fault in BusGen27'
    ↪ ,'Fault in
```

```
BusGen28','Fault in BusGen29','Fault in Bus24','Fault in Bus25','
    ↪ Fault in Bus26',
'Fault in Bus27','Fault in Bus28','Fault in Bus29'};
%%%%%Select Zone to Study%%%%%%%%
AreaSel=menu('Select an Area to Perform the Study','Area North','Area
    ↪  Central',
'Area South','ALL');
Ars = AreaSel-1;
%%%%%%% North %%%%
if Ars == 0
    OptK=zeros(1,62);
    Assig=zeros(21,62);
for i = 1:18
    AAX = sprintf('P_BusFault_Case_%d.out', i);
    AAi=importdata(AAX,' ');
    AAx1=AAi.data;
    AA=AAx1(:,10:size(AAx1,2));
      %%%select the correct heads for the data%%%
        heady=strsplit(AAi.textdata{1},' ');
        heady2=heady(1, 2:2:end);
      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            headx1 = strrep(head,'"','');
        head = headx1(1, 10:size(headx1,2));
       clearvars head1 head2 head3 head4 heady heady2
       %%%%
        %head=A.Properties.VariableNames;
        %head(:, 1) = [];
        element=size(AA,2);
        x = AAi.data(:,1);
        y=AA(:,1:element);
        %normalize signals
        yy = bsxfun(@times, bsxfun(@minus,y,min(y)), 1./range(y));
        Aedit=[x yy];
        A1=transpose(Aedit);
        a1=size(A1,1);
        A2=A1(2:a1,:);
%Calculate the distance, (just for later comparison)
        Dist = pdist(A2,'euclidean');
%Calculate hierarchical clusters of the rows of the data based on the
%euclidean distance (just for comparison)
        Z=linkage(A2);
        tic
%call the function opt_kmeans to find the optimal numbe of clusters
        [IDX,C,SUMD,K]=opt_kmeans(A2);
        %clusty = cluster(Z,'maxclust',K); %%para comprobar los
```

```
            ↪ clusters no
        %necesario al momento
        Assig(:,i)=IDX;
        OptK(:,i)=K;
        toc
 plot(x,yy(:,1), x,yy(:,2), x,yy(:,3),x,yy(:,4),x,yy(:,5),x,yy(:,6),x
     ↪ ,yy(:,7),x,yy(:,8),x,
 yy(:,9),x,yy(:,10),x,yy(:,11),x,yy(:,12),x,yy(:,13),x,yy(:,14),x,yy
     ↪ (:,15),x,yy(:,16),x,
 yy(:,17),x,yy(:,18),x,yy(:,19),x,yy(:,20),x,yy(:,21))
legend(head);
saveas(1,sprintf('P_BusFault_North_%d.png',i));
i
end
i
Fin1=[OptK;Assig];
Fin2=[Fin1(:,1:18) Fin1(:,26)];
headtr=transpose(head);
headtr=['K';headtr];
Fin3=num2cell(Fin2);
Fin4=[headtr Fin3];

NameUp=['K' FinHead(1:18) FinHead(1,26)];
%Names=Casesmat(1,1:9); %%
%NameUp=num2cell(Names);
Fin=[NameUp;Fin4];

save('P_BusFault_North.mat','Fin');
 filename = 'P_BusFault_North.xlsx';
xlswrite(filename,Fin);
```

7.2. ANNEX: INITIAL PARAMETER TABLES

Table 7.1: Load Input Table

BASE LINE LOADS SET IN RTDS								
Load	**L01**	**L02**	**L03**	**L04**	**L05**	**L06**	**L07**	**L08**
P set	525	525	525	525	525	525	525	525
P min	262.5	262.5	262.5	262.5	262.5	262.5	262.5	262.5
Pmax	787.5	787.5	787.5	787.5	787.5	787.5	787.5	787.5
Qset	110.25	0	110.25	110.25	110.25	110.25	110.25	110.25
Qmin	55.125	0	55.125	55.125	55.125	55.125	55.125	55.125
Qmax	165.375	0	165.375	165.375	165.375	165.375	165.375	165.375
Load	**L09**	**L10**	**L11**	**L12**	**L13**	**L14**	**L15**	**L16**
P set	3250	3250	3250	2166.67	2166.67	2166.67	2166.67	3250
P min	1625	1625	1625	1083.33	1083.33	1083.33	1083.33	1625
Pmax	4875	4875	4875	3250	3250	3250	3250	4875
Qset	682.5	682.5	682.5	455	455	455	455	682.5
Qmin	341.25	341.25	341.25	227.5	227.5	227.5	227.5	341.25
Qmax	1023.75	1023.75	1023.75	682.5	682.5	682.5	682.5	1023.75
Load	**L17**	**L18**	**L19**	**L20**	**L21**	**L22**	**L23**	**L24**
P set	2166.67	2166.67	1875	1875	2055.56	2055.56	2055.56	2055.56
P min	1083.33	1083.33	937.5	937.5	1027.78	1027.78	1027.78	1027.78
Pmax	3250	3250	2812.5	2812.5	3083.33	3083.33	3083.33	3083.33
Qset	455	455	393.75	393.75	431.67	431.67	431.67	0
Qmin	227.5	227.5	196.875	196.875	215.835	215.835	215.835	0
Qmax	682.5	682.5	590.625	590.625	647.505	647.505	647.505	0
Load	**L25**	**L26**	**L27**	**L28**	**L29**			
P set	2055.56	2055.56	2055.56	2055.56	2055.56			
P min	1027.78	1027.78	1027.78	1027.78	1027.78			
Pmax	3083.33	3083.33	3083.33	3083.33	3083.33			
Qset	431.67	431.67	431.67	431.67	431.67			
Qmin	215.835	215.835	215.835	215.835	215.835			
Qmax	647.505	647.505	647.505	647.505	647.5			

Table 7.2: Transmission Line Parameter

Line	Dist[km]	Req [ohm/km]	Ceq[uF/km]	X’eq[ohm/km]	Line	Dist[km]	Req [ohm/km]	Ceq[uF/km]	X’eq[ohm/km]
Line1-2_1	1	9.23	1.197068	15.13	Line20-21_2	1	1.92	0.8845195	7.68
Line1-2_2	1	9.23	0.360295	15.13	Line20-26_1	1	0.56	0.4474164	3.68
Line1-3_1	1	2.645	0.4377398	56.72	Line20-26_2	1	0.56	0.4474164	3.68
Line1-3_2	1	2.645	0.4377398	56.72	Line21-22_1	1	0.77	0.6049798	9.76
Line10-15_1	1	0.83	2.115965	10.08	Line21-22_2	1	0.3	0.2450986	1.78
Line10-15_2	1	0.85	10.68926	13.36	Line21-25_1	1	0.4	0.3155406	16
Line11-12_1	1	0.16	0.158773	13.6	Line21-25_2	1	0.4	0.3155406	16
Line11-12_2	1	0.16	0.158773	13.6	Line22-23_1	1	0.62	0.490611	4.8
Line11-13_1	1	0.64	0.529986	8.32	Line22-23_2	1	0.88	0.6899367	4.8
Line11-13_2	1	0.64	0.4969772	8.32	Line22-25_1	1	0.54	0.8534843	6.56
Line11-15-2	1	1.12	0.7772809	67.2	Line22-25_2	1	0.59	0.8152871	6.56
Line11-15_1	1	1.58	1.141555	67.2	Line23-24_1	1	0.37	5.659359	1.12
Line12-13_1	1	1.54	0.7659491	17.25	Line23-24_2	1	1.38	1.914252	1.28
Line12-13_2	1	1.54	0.7659491	17.25	Line23-29_1	1	2.42	1.054402	29.12
Line12-18-2	1	1.18	0.579133	14.4	Line23-29_2	1	2.42	1.054402	29.12
Line12-18_1	1	1.55	0.762957	14.4	Line24-25_1	1	1.66	0.5805336	14.56
Line13-14_1	1	1.71	2.336586	18.61	Line24-25_2	1	1.66	0.5805336	14.56
Line13-14_2	1	1.31	2.412184	19.22	Line24-28_1	1	1.09	0.4750775	11.2
Line13-15_1	1	2.62	0.2196338	36.8	Line24-28_2	1	1.09	0.4750775	11.2
Line13-15_2	1	2.19	1.321591	36.8	Line25-26_1	1	0.32	1.05838	9.12
Line13-18_1	1	1.34	1.543612	11.2	Line25-26_2	1	0.32	1.05838	9.12
Line13-18_2	1	0.78	0.3865555	11.2	Line26-27_1	1	0.32	0.3574938	8.05
Line14-15_1	1	0.29	1.108705	3.55	Line26-27_2	1	0.32	0.3574938	8.05
Line14-15_2	1	0.3	1.51038	3.55	Line27-28_1	1	0.61	0.5964491	11.38
Line14-16_1	1	8	0.2916673	28.8	Line27-28_2	1	0.61	0.5964491	11.38
Line14-16_2	1	0.8	0.5560555	25.6	Line28-29_1	1	0.82	0.6764085	12.74
Line15-16_1	1	0.13	1.5883664	1.375	Line28-29_2	1	0.82	0.6764085	12.74
Line15-16_2	1	0.265	1.4061658	4.16	Line3-4_1	1	2.27	0.1851927	31.01
Line16-17_1	1	1.6	0.9097615	17.15	Line3-4_2	1	2.27	0.01852564	31.01
Line16-17_2	1	1.6	0.5274076	17.15	Line4-5_1	1	1.6	0.2486955	38.4
Line16-19_1	1	0.9	0.8944508	22.56	Line4-5_2	1	1.6	0.2486955	38.4
Line16-19_2	1	0.9	0.8944508	22.56	Line4-6_1	1	2.08	0.3497589	36.8
Line16-21_1	1	2.32	1.824107	29.18	Line4-6_2	1	2.08	0.2976197	36.8
Line16-21_2	1	2.32	1.824107	29.18	Line4-7_1	1	3.38	0.2335758	21.6
Line16-22_1	1	2.85	1.247393	27.52	Line4-7_2	1	3.36	0.3059913	21.6
Line16-22_2	1	2.85	1.671732	27.52	Line5-6_1	1	1.36	0.7610471	16.82
Line17-18_1	1	0.67	0.4673107	2.88	Line5-6_2	1	2.42	1.179657	25.81
Line17-18_2	1	0.67	0.4673107	2.88	Line6-7_1	1	4.8	0.5847034	320
Line17-22_1	1	1.1	0.9099843	15.52	Line6-7_2	1	4.8	0.5847034	320
Line17-22_2	1	1.09	0.9083928	15.52	Line6-9_1	1	1.25	0.9221119	13.63
Line18-23_1	1	1.87	0.8200618	15.36	Line6-9_2	1	1.25	0.1466135	13.63
Line18-23_2	1	2.21	0.960691	15.36	Line7-8_1	1	0.213333333	7.682409	0.053333333
Line19-20_1	1	2.11	0.7273381	22.88	Line7-8_2	1	0.213333333	4.34493	0.053333333
Line19-20_2	1	2.85	1.329358	34.08	Line8-10_1	1	1.33	1.317803	28
Line19-21_1	1	0.59	0.5878865	9.44	Line8-10_2	1	1.33	1.317803	28
Line19-21_2	1	0.59	0.5848944	9.44	Line9-10_1	1	7.87	0.497773	54.88
Line2-3	1	22.72	0.05220282	58.23	Line9-10_2	1	5.63	0.377611	39.25
Line2-4_1	1	0.15	3.749436	24.58	Line9-11_1	1	2.62	0.9684578	26.08
Line2-4_2	1	0.15	4.667824	24.58	Line9-11_2	1	2.62	0.9684578	26.08
Line20-21_1	1	1.92	1.392606	7.68					

Table 7.3: Buses Distribution in Areas

Area 1			**Area 2**			**Area 3**		
Case	Subsystem	Bus	Case	Subsystem	Bus	Case	Subsystem	Bus
1	Sub #1	FLGT1	19	Sub #2	FLG10	37	Sub #3	FLGT19
2	Sub #1	FLGT2	20	Sub #2	FLG11	38	Sub #3	FLGT20
3	Sub #1	FLGT3	21	Sub #2	FLGT9	39	Sub #3	FLGT21
4	Sub #1	FLGT4	22	Sub #2	FLGT12	40	Sub #3	FLGT22
5	Sub #1	FLGT5	23	Sub #2	FLGT13	41	Sub #3	FLGT23
6	Sub #1	FLGT6	24	Sub #2	FLGT14	45	Sub #3	FLN19
7	Sub #1	FLGT7	25	Sub #2	FLGT15	46	Sub #3	FLN20
8	Sub #1	FLN1	27	Sub #2	FLN09	47	Sub #3	FLN21
9	Sub #1	FLN2	28	Sub #2	FLN10	48	Sub #3	FLN22
10	Sub #1	FLN3HV	29	Sub #2	FLN11	49	Sub #3	FLN23
11	Sub #1	FLN3LV	30	Sub #2	FLN12	51	Sub #4	FLGT24
12	Sub #1	FLN4HV	31	Sub #2	FLN13	52	Sub #4	FLGT25
13	Sub #1	FLN4LV	32	Sub #2	FLN14	53	Sub #4	FLGT26
14	Sub #1	FLN5	33	Sub #2	FLN15	54	Sub #4	FLGT27
15	Sub #1	FLN6	34	Sub #3	FLGT16	55	Sub #4	FLGT28
16	Sub #1	FLN7	35	Sub #3	FLGT17	56	Sub #4	FLGT29
17	Sub #1	FLPS13	36	Sub #3	FLGT18	57	Sub #4	FLN24
18	Sub #2	FLG08	42	Sub #3	FLN16	58	Sub #4	FLN25
26	Sub #2	FLN8	43	Sub #3	FLN17	59	Sub #4	FLN26
			44	Sub #3	FLN18	60	Sub #4	FLN27
						61	Sub #4	FLN28
						62	Sub #4	FLN29

7.3. ANNEX: TABLES GONE GREEN SCENARIOS

Table 7.4: GONE GREEN 2020 [4]

GONE GREEN 2020							
Region	Substation	Sync Gen (GW)	Wind Gen (GW)	Active Load (GW)	Reactive Load (MVAr)	Dispatch Wind (GW)	Dispatch Sync (GW)
Scotland	1	1.08	0.85033	0.5000	105.00	0.856	0.9639
	2	0	0.85	0.5000	105.00	0.8598	0
	3	1.08	0.85	0.5000	105.00	0.8415	0.9639
	4	0	0.85	0.5000	105.00	0.8413	0
	5	1.08	0.85	0.5000	105.00	0.8415	0.9639
	6	0	0.85	0.5000	105.00	0.8415	0
	7	1.08	0.85	0.5000	105.00	0.8415	0.9639
	8	1.08	0.65	0.5000	105.00	0.6435	0.9639
North England	9	1.512	1.558	3.0000	630.00	1.54242	1.34946
	10	3.78	1.558	3.0000	630.00	1.54242	1.9845
	11	3.78	1.558	3.0000	630.00	1.54242	3.37365
	16	3.78	0.725	3.0000	630.00	0.71775	3.37365
West England	12		0.2	2.0000	420.00	0.198	0
	13	2.639	0	2.0000	420.00	0	1.939665
	14		0.2	2.0000	420.00	0.198	0
	15	3.77	0	2.0000	420.00	0	3.364725
	17		0.2	2.0000	420.00	0.198	0
	18	3.77	0	2.0000	420.00	0	2.77095
East England	19	1.755	1.3495	1.8750	393.75	1.336005	1.10565
	20	1.95	1.35	1.8750	393.75	1.3365	1.2285
South England	21	0.756	0.3	1.8889	396.67	0.297	0.59535
	22	1	0	1.8889	396.67	0	0.7875
	23	1	0.497	1.8889	396.67	0.49203	0.7875
	24	1	0	1.8889	396.67	0	0.7875
	25	1	0	1.8889	396.67	0	0.7875
	26	1	0.504	1.8889	396.67	0.49896	0.7875
	27	1	0	1.8889	396.67	0	0.7875
	28	1	0	1.8889	396.67	0	0.7875
	29	1	0.4995	1.8889	396.67	0.494505	0.945

Table 7.5: GONE GREEN 2025[4]

GONE GREEN 2025							
Region	Substation	Sync Gen (GW)	Wind Gen (GW)	Active Load (GW)	Reactive Load (MVAr)	Dispatch Wind (GW)	Dispatch Sync (GW)
Scotland	1	0.864	1.85033	0.51	107.63	1.8318267	0
	2	0	1.85	0.51	107.63	1.8315	0
	3	1.08	1.85	0.51	107.63	1.8315	0
	4	0	1.85	0.51	107.63	1.8315	0
	5	1.08	1.85	0.51	107.63	1.8315	0
	6	0	2.218	0.51	107.63	2.19582	0
	7	1.08	1.1141	0.51	107.63	1.102959	0
	8	1.08	2.018	0.51	107.63	1.99782	0
North England	9	0	2.658	3.00	630.00	2.63142	0
	10	3.024	2.56	3.00	630.00	2.5344	0.0603288
	11	3.78	2.56	3.00	630.00	2.5344	1.9845
	16	3.78	0.725	3.00	630.00	0.71775	1.9845
West England	12	0	1.9	2.00	420.00	1.881	0
	13	2.268	0	2.00	420.00	0	1.66698
	14	0	0.2	2.00	420.00	0.198	0
	15	3.77	0	2.00	420.00	0	3.364725
	17	0	0.2	2.00	420.00	0.198	0
	18	3.77	0	2.00	420.00	0	2.968875
East England	19	1.85	2.4995	1.88	393.75	2.474505	0
	20	2.145	2.5	1.88	393.75	2.475	0.1126125
South England	21	0.648	0.4	1.94	408.33	0.396	0.3402
	22	1	0	1.94	408.33	0	0.525
	23	1	0.497	1.94	408.33	0.49203	0.525
	24	1	0	1.94	408.33	0	0.63
	25	1	0	1.94	408.33	0	0.63
	26	1	0.504	1.94	408.33	0.49896	0.7875
	27	1	0	1.94	408.33	0	0.7875
	28	1	0	1.94	408.33	0	0.7875
	29	1	0.4995	1.94	408.33	0.494505	0.945

Table 7.6: GONE GREEN 2030[4]

GONE GREEN 2030							
Region	Substation	Sync Gen (GW)	Wind Gen (GW)	Active Load (GW)	Reactive Load (MVAr)	Dispatch Wind (GW)	Dispatch Sync (GW)
Scotland	1	0	1.85033	0.55	115.50	1.8318267	0
	2	0	1.85	0.55	115.50	1.8315	0
	3	0.864	0.85	0.55	115.50	0.8415	0
	4	0	0	0.55	115.50	0	0
	5	1.08	1.85	0.55	115.50	1.8315	0
	6	0	2.218	0.55	115.50	2.19582	0
	7	1.08	0	0.55	115.50	0	0
	8	1.08	2.291	0.55	115.50	2.26809	0
North England	9	0	2.658	3.13	656.25	2.63142	0
	10	1.512	3.35	3.13	656.25	3.3165	0.31752
	11	3.78	2.56	3.13	656.25	2.5344	0.7938
	16	3.78	2.332	3.13	656.25	2.30868	0.7938
West England	12	0	1.9	2.17	455.00	1.881	0
	13	2.18	1	2.17	455.00	0.99	1.6023
	14	0	1.2	2.17	455.00	1.188	0
	15	4.158	0.95	2.17	455.00	0.9405	2.26275
	17	0	0.2	2.17	455.00	0.198	0
	18	4.536	0.95	2.17	455.00	0.9405	3.394125
East England	19	2.34	4.1	2.00	420.00	4.059	0
	20	3.12	6.4	2.00	420.00	6.336	0
South England	21	0	0.4	2.11	443.33	0.396	0
	22	0	0.53	2.11	443.33	0.5247	0
	23	1	0.497	2.11	443.33	0.49203	0
	24	1	0	2.11	443.33	0	0.18375
	25	1	0	2.11	443.33	0	0.63
	26	1	0.504	2.11	443.33	0.49896	0
	27	1	0.53	2.11	443.33	0.5247	0.63
	28	1	0.53	2.11	443.33	0.5247	0.63
	29	1	0.4995	2.11	443.33	0.494505	0.63

Table 7.7: GONE GREEN 2035[4]

GONE GREEN 2035							
Region	Substation	Sync Gen (GW)	Wind Gen (GW)	Active Load (GW)	Reactive Load (MVAr)	Dispatch Wind (GW)	Dispatch Sync (GW)
Scotland	1	0	3.00033	0.60	126.00	2.9703267	0
	2	0	2.85	0.60	126.00	2.8215	0
	3	0.864	0	0.60	126.00	0	0
	4	0	0	0.60	126.00	0	0
	5	1.296	1.85	0.60	126.00	1.8315	0
	6	0	2.7	0.60	126.00	2.673	0
	7	1.08	1.85	0.60	126.00	1.8315	0
	8	1.08	2.45	0.60	126.00	2.4255	0
North England	9	0	4.4	3.38	708.75	4.356	0
	10	0.756	4.3	3.38	708.75	4.257	0.2730672
	11	3.78	3.7	3.38	708.75	3.663	0
	16	3.78	2.3	3.38	708.75	2.277	0
West England	12	0	3.4	2.33	490.00	3.366	0
	13	0	1	2.33	490.00	0.99	0
	14	0	1.9	2.33	490.00	1.881	0
	15	2.268	1.75	2.33	490.00	1.7325	0
	17	0	0.2	2.33	490.00	0.198	0
	18	4.158	1.05	2.33	490.00	1.0395	2.18295
East England	19	2.145	6.3995	2.13	446.25	6.335505	0
	20	3.15	6.4	2.13	446.25	6.336	0
South England	21	0	0.4	2.28	478.33	0.396	0
	22	0	0.53	2.28	478.33	0.5247	0
	23	1.296	0.497	2.28	478.33	0.49203	0
	24	1	0.53	2.28	478.33	0.5247	0
	25	1	0.53	2.28	478.33	0.5247	0
	26	1	0.504	2.28	478.33	0.49896	0
	27	0	0.60475	2.28	478.33	0.5987025	0
	28	1	0.60475	2.28	478.33	0.5987025	0
	29	1	0.4995	2.28	478.33	0.494505	0

Table 7.8: CLuster Elements Z1

L01	
Clusters	6
PG09	3
PG10	6
PG11	3
PG12	6
PG13	5
PG14	6
PG15	5
PG16	6
PG17	5
PG18	3
PG19	5
PG20	4
PG21	3
PG22	2
PG23	2
PG24	2
PG25	2
PG26	1
PG27	2
PG28	2
PG29	1

7.4. ANNEX: ASSIGNATION CLUSTERING TABLES

Table 7.9: Clustering by P as a response of Bus Faults in the North Area

Clustering by P as a response of Bus Faults in the North Area

	Bus G1	Bus G2	Bus G3	Bus G4	Bus G5	Bus G6	Bus G7	Bus 1	Bus 2	Bus 3HV	Bus 3LV	Bus 4HV	Bus 4LV	Bus 5	Bus 6	Bus7	FLPS 13	FL G08	Bus 8
K	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Z9	4	2	3	3	5	5	2	1	1	5	5	3	2	4	3	4	3	5	5
Z10	1	5	5	5	1	2	4	4	4	2	3	1	5	3	2	2	2	1	2
Z11	4	2	3	3	5	5	2	1	1	5	5	3	2	4	3	4	3	5	5
Z12	2	3	4	2	3	1	1	5	2	3	2	2	4	2	1	4	5	4	1
Z13	3	4	3	3	5	4	2	1	1	1	4	4	4	5	3	1	3	3	5
Z14	2	3	4	2	3	1	1	5	2	3	2	2	4	2	1	4	5	4	1
Z15	3	4	3	3	5	4	2	1	1	1	4	4	4	5	3	1	3	3	5
Z16	2	3	4	2	3	1	1	5	2	3	2	2	2	2	1	4	5	4	1
Z17	3	4	2	3	4	3	5	2	5	4	2	4	2	5	4	3	3	2	4
Z18	5	4	2	4	1	2	4	4	4	2	3	5	5	3	4	2	1	1	2
Z19	5	1	4	2	3	1	1	5	2	3	2	2	2	2	1	4	5	4	1
Z20	3	4	2	3	5	3	5	1	5	4	2	4	2	5	4	3	3	2	4
Z21	1	5	5	1	2	2	3	4	3	2	3	1	1	1	2	2	2	1	3
Z22	1	5	5	5	2	2	3	4	4	2	3	1	5	3	2	2	2	1	3
Z26	1	5	1	5	2	2	3	3	4	2	1	1	3	3	5	5	4	1	3
Z27	1	5	5	5	2	2	3	4	4	2	3	1	5	3	2	2	2	1	3
Z28	1	5	5	5	2	2	3	4	4	2	3	1	5	3	2	2	2	1	3
Z29	1	5	1	5	2	2	3	3	4	2	1	1	3	3	5	5	4	1	3

Table 7.10: Clustering by P as a response of Bus Faults in the Center Area

Clustering by P as a response of Bus Faults in the Center Area

	FL G10	FL G11	Bus G 9	Bus G12	Bus G13	Bus G14	Bus G15	Bus 09	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14	Bus 15	Bus G16	Bus G17	Bus G18	Bus 16	Bus 17	Bus 18
K	7	8	7	8	8	8	7	7	8	7	8	8	8	8	7	7	8	7	8	8
Z1	2	4	4	1	5	7	5	7	5	7	8	4	4	3	1	2	8	5	1	5
Z2	3	5	4	2	6	7	6	3	8	2	8	7	8	4	6	3	5	5	8	7
Z3	1	8	5	5	8	3	2	2	6	5	1	6	3	2	7	6	2	2	7	2
Z4	4	7	7	6	1	1	4	5	6	1	1	6	3	2	7	1	4	2	5	2
Z5	5	2	2	4	7	6	6	6	4	3	4	3	6	5	5	3	7	7	6	4
Z6	6	6	3	3	2	5	1	4	7	7	5	8	1	1	2	4	6	6	2	3
Z7	7	3	6	4	3	2	6	6	2	7	3	5	6	5	5	7	7	4	6	4
Z8	2	6	6	4	3	2	7	6	1	6	3	2	6	5	4	3	3	3	3	8
Z19	2	6	4	2	2	5	3	3	1	7	7	1	1	8	3	5	6	6	2	3
Z20	2	6	4	2	2	5	6	3	1	7	7	1	1	8	5	3	6	6	2	3
Z21	1	1	1	7	4	4	2	1	3	4	6	6	2	6	7	1	1	1	4	1
Z22	1	1	1	7	4	4	2	1	3	1	2	6	7	6	7	1	4	1	4	1
Z23	1	1	1	7	4	4	2	1	3	1	2	6	7	6	7	1	4	1	4	1
Z24	4	7	7	8	1	8	4	5	6	1	1	6	5	7	7	1	4	2	5	6
Z25	1	1	1	7	4	4	2	1	3	1	2	6	7	6	7	1	4	1	4	1
Z26	4	7	7	8	1	1	4	5	6	1	1	6	3	2	7	1	4	2	5	2
Z27	1	1	1	7	4	4	2	1	3	1	2	6	7	6	7	1	4	1	4	1
Z28	1	1	1	7	4	4	2	1	3	1	2	6	7	6	7	1	4	1	4	1
Z29	4	7	7	8	1	1	4	5	6	1	1	6	3	2	7	1	4	2	5	2

Table 7.11: Clustering by P as a response of Bus Faults in the South Area

Clustering by P as a response of Bus Faults in the South Area																						
	Bus G19	**Bus G20**	**Bus G21**	**Bus G22**	**Bus G23**	**Bus 19**	**Bus 20**	**Bus 21**	**Bus 22**	**Bus 23**	**Bus G24**	**Bus G25**	**Bus G26**	**Bus G27**	**Bus G28**	**Bus G29**	**Bus 24**	**Bus 25**	**Bus 26**	**Bus 27**	**Bus 28**	**Bus 29**
K	9	9	10	9	9	9	9	9	9	10	9	9	10	10	10	9	9	9	9	9	10	9
Z1	8	2	5	9	4	7	5	3	7	6	1	4	3	10	7	9	5	1	5	7	6	1
Z2	1	1	6	6	3	9	5	6	1	4	3	4	4	7	9	1	6	6	6	6	10	9
Z3	6	6	1	8	5	1	2	9	9	10	2	7	1	2	8	8	3	2	8	8	7	5
Z4	6	7	9	2	5	8	7	9	9	9	6	5	1	1	8	2	9	3	3	8	4	9
Z5	8	1	3	6	4	4	3	3	2	4	7	4	6	6	9	1	1	9	6	3	1	9
Z6	4	1	8	4	8	4	1	1	4	1	8	1	2	5	6	4	5	1	1	2	8	4
Z7	8	1	10	3	4	3	9	2	2	8	3	4	5	9	10	3	5	8	6	2	9	9
Z8	9	5	7	5	1	5	8	7	5	7	4	8	8	4	2	1	8	7	6	1	5	2
Z9	8	1	7	6	4	4	5	3	2	4	3	4	3	6	9	1	5	1	7	2	1	9
Z10	3	4	4	2	7	6	4	9	6	3	6	3	1	8	3	7	4	5	3	5	2	8
Z11	8	1	7	6	4	4	5	3	2	4	3	4	3	6	9	1	5	1	7	2	1	9
Z12	5	9	2	1	6	2	6	5	8	2	5	2	10	3	1	6	2	4	4	9	3	3
Z13	7	1	7	4	2	4	1	8	4	5	8	9	9	6	5	5	5	1	1	2	1	6
Z14	5	9	2	1	6	2	6	5	8	2	5	2	10	3	1	6	2	4	4	4	3	3
Z15	7	1	7	4	2	4	1	8	4	5	8	9	9	6	5	5	5	1	1	2	1	6
Z16	5	3	2	1	6	2	6	5	3	2	5	2	10	3	1	6	2	4	9	4	3	7
Z17	2	8	3	5	1	5	8	7	5	7	9	6	7	4	4	5	7	7	1	1	5	2
Z18	3	4	4	7	9	6	4	4	6	3	6	3	1	8	3	7	4	5	2	5	2	8

Table 7.12: Clustering by P as a Response of Line Switching in the North Area

Clustering by P as a Response of Line Switching in the North Area																									
	L0102A	**L0102B**	**L0103A**	**L0103B**	**L0203A**	**L0204A**	**L0204B**	**L0304A**	**L0304B**	**L0405A**	**L0405B**	**L0406A**	**L0406B**	**L0407A**	**L0407B**	**L0506A**	**L0506B**	**L0607A**	**L0607B**	**L0609A**	**L0609B**	**L0708A**	**L0708B**	**L0810A**	**L0810B**
K	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Z09	3	5	3	3	1	4	1	4	4	5	3	2	3	4	5	5	3	5	4	1	2	2	3	3	1
Z10	2	2	1	2	4	2	2	1	1	1	2	1	2	1	2	2	2	2	3	4	1	1	5	2	5
Z11	3	5	3	1	1	3	1	4	4	5	3	2	3	4	5	1	3	3	4	1	2	2	3	3	1
Z12	1	4	5	2	4	2	2	1	1	1	2	1	2	1	2	2	2	2	3	4	1	1	5	2	5
Z13	4	5	3	3	1	5	1	4	4	3	5	2	1	4	4	5	3	4	4	5	2	4	3	5	4
Z14	1	4	5	2	4	2	2	1	1	1	2	1	2	1	2	2	2	2	3	4	1	1	5	2	5
Z15	4	5	3	3	1	5	1	4	4	3	5	2	1	4	4	5	3	4	4	5	2	4	3	5	4
Z16	1	4	2	2	4	2	2	1	1	1	2	1	2	1	2	2	2	2	3	4	1	1	5	2	5
Z17	4	3	3	5	5	5	1	4	4	5	4	5	4	4	3	4	1	4	5	5	3	4	3	4	1
Z18	2	2	4	4	1	4	3	5	4	2	5	2	4	4	5	5	4	1	1	1	5	3	3	3	1
Z19	1	4	2	4	1	4	1	4	4	5	5	2	4	4	5	5	4	5	5	1	2	4	4	3	1
Z20	4	3	3	4	1	4	5	3	5	5	5	4	4	2	5	5	5	5	5	1	4	5	4	3	1
Z21	5	1	1	3	1	4	1	4	4	5	5	2	3	4	5	5	4	5	4	1	2	4	3	3	1
Z22	2	1	1	2	2	2	2	1	2	1	2	1	2	5	2	2	2	2	3	3	1	1	2	2	3
Z23	2	1	1	2	2	2	2	1	2	1	2	1	2	5	2	2	2	2	3	3	1	1	2	2	3
Z24	2	1	1	2	2	2	2	1	2	1	2	1	2	5	2	2	2	2	3	3	1	1	2	2	3
Z25	2	1	1	2	2	2	2	1	2	1	2	1	2	5	2	2	2	2	3	3	1	1	2	2	3
Z26	2	1	1	3	3	1	4	2	3	4	1	3	5	3	1	3	4	5	2	2	2	4	1	1	2
Z27	2	1	1	2	2	2	2	1	2	1	2	1	2	5	2	2	2	2	3	3	1	1	2	2	3
Z28	2	1	1	2	2	2	2	1	2	1	2	1	2	5	2	2	2	2	3	3	1	1	2	2	3

Table 7.13: Clustering by P as a Response of Line Switching in the Center Area part1

Clustering by P as a Response of Line Switching in the Center Area part1																					
	L09 10A	**L09 10B**	**L09 11A**	**L09 11B**	**L10 15A**	**L10 15B**	**L11 12A**	**L11 12B**	**L11 13A**	**L11 13B**	**L11 15A**	**L11 15B**	**L12 13A**	**L12 13B**	**L12 18A**	**L12 18B**	**L13 14A**	**L13 14B**	**L13 15A**	**L13 15B**	**L13 18A**
K	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Z1	1	1	6	3	7	6	1	6	2	4	3	7	5	3	2	7	1	5	7	3	2
Z2	6	2	3	6	2	3	6	6	4	7	4	7	4	5	7	5	5	6	4	7	5
Z3	2	1	1	2	2	2	6	3	5	6	1	5	3	4	7	5	5	1	4	4	1
Z4	7	5	3	5	1	7	2	7	6	1	1	4	7	4	4	3	6	2	3	4	7
Z5	4	1	5	7	2	1	6	2	5	4	1	2	3	6	1	1	5	7	4	5	6
Z6	5	6	3	6	6	7	7	4	1	5	7	5	1	1	7	3	7	1	1	4	4
Z7	7	3	3	5	1	7	2	7	6	1	1	4	6	4	4	3	6	2	3	4	7
Z8	4	1	5	6	2	5	6	6	7	3	6	7	3	7	5	5	4	1	5	6	3
Z19	5	6	3	6	6	7	7	4	1	5	7	5	1	1	7	3	7	1	1	4	4
Z20	3	7	7	4	4	7	3	5	1	4	1	3	1	4	7	2	5	1	6	4	6
Z21	1	1	3	6	2	7	7	6	1	4	1	7	3	4	7	3	5	1	1	4	2
Z22	1	4	2	1	3	4	4	1	3	2	2	1	2	2	3	4	3	3	2	1	2
Z23	1	4	2	1	3	4	4	1	3	2	2	1	2	2	3	4	3	3	2	1	2
Z24	1	4	2	1	3	4	4	1	3	2	2	1	2	2	3	4	3	3	2	1	2
Z25	1	4	2	1	3	4	4	1	3	2	2	1	2	2	3	4	3	3	2	1	2
Z26	2	1	4	2	5	2	5	3	5	6	5	6	3	4	6	6	2	4	4	2	1
Z27	1	4	2	1	3	4	4	1	3	2	2	1	2	2	3	4	3	3	2	1	2
Z28	1	4	2	1	3	4	4	1	3	2	2	1	2	2	3	4	3	3	2	1	2
Z29	2	1	4	2	5	2	5	3	5	6	5	6	3	4	6	6	2	4	4	2	1

Table 7.14: Clustering by P as a Response of Line Switching in the Center Area part2

Clustering by P as a Response of Line Switching in the Center Area part2																					
	L13 18B	**L14 15A**	**L14 15B**	**L14 16A**	**L14 16B**	**L15 16A**	**L15 16B**	**L16 17A**	**L16 17B**	**L16 19A**	**L16 19B**	**L16 21A**	**L16 21B**	**L16 22A**	**L16 22B**	**L17 18A**	**L17 18B**	**L17 22A**	**L17 22B**	**L18 23A**	**L18 23B**
K	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Z1	2	6	6	6	7	1	6	6	5	4	3	6	5	4	6	1	2	1	5	7	1
Z2	5	5	4	4	1	4	2	7	6	3	4	7	3	3	7	3	4	2	7	2	5
Z3	5	5	7	4	1	2	7	5	6	1	6	1	3	3	4	2	5	2	3	2	5
Z4	6	4	4	1	5	7	1	3	4	5	7	4	7	7	4	6	1	2	4	5	4
Z5	4	5	1	3	6	5	7	2	4	7	6	4	3	6	2	7	6	6	3	7	5
Z6	7	7	7	6	1	2	4	1	7	2	7	1	5	5	1	4	7	5	3	7	3
Z7	6	3	4	7	5	7	1	3	4	5	7	4	7	7	4	6	1	2	4	5	4
Z8	4	5	4	6	3	3	7	1	3	7	1	3	1	3	4	2	6	7	3	1	7
Z19	7	7	7	6	1	2	4	1	7	2	7	1	5	5	1	4	7	5	3	7	3
Z20	7	7	2	6	1	2	5	1	7	6	5	1	4	3	4	5	3	3	6	4	6
Z21	4	5	4	6	1	2	4	1	4	4	7	4	5	3	4	2	2	2	3	7	5
Z22	1	1	5	5	2	1	3	4	1	4	2	5	2	2	3	1	2	1	1	3	1
Z23	1	1	5	5	2	1	3	4	1	4	2	5	2	2	3	1	2	1	1	3	1
Z24	1	1	5	5	2	1	3	4	1	4	2	5	2	2	3	1	2	1	1	3	1
Z25	1	1	5	5	2	1	3	4	1	4	2	5	2	2	3	1	2	1	1	3	1
Z26	3	2	3	2	4	6	7	5	2	1	6	2	6	1	5	2	5	4	2	6	2
Z27	1	1	5	5	2	1	3	4	1	4	2	5	2	2	3	1	2	1	1	3	1
Z28	1	1	5	5	2	1	3	4	1	4	2	5	2	2	3	1	2	1	1	3	1
Z29	3	2	3	2	4	6	7	5	2	1	6	2	6	1	5	2	5	4	2	6	2

Table 7.15: Clustering by P as a Response of Line Switching in the South Area part1

Clustering by P as a Response of Line Switching in the South Area part1																					
	L16 19A	**L16 19B**	**L16 21A**	**L16 21B**	**L16 22A**	**L16 22B**	**L17 22A**	**L17 22B**	**L18 23A**	**L18 23B**	**L19 20A**	**L19 20B**	**L19 21A**	**L19 21B**	**L20 21A**	**L20 21B**	**L20 26A**	**L20 26B**	**L21 22A**	**L21 22B**	**L21 25A**
K	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Z1	2	6	7	3	1	8	5	7	1	6	3	2	6	7	3	3	4	5	8	6	3
Z2	4	1	2	1	3	2	7	2	2	2	5	8	7	3	6	1	8	7	3	3	4
Z3	6	4	1	1	6	2	3	5	2	5	5	4	2	3	5	4	8	8	5	5	4
Z4	7	2	1	6	2	6	6	4	5	5	1	1	1	4	5	7	8	3	4	5	4
Z5	8	4	8	7	6	4	2	6	7	8	7	4	2	3	5	8	2	2	1	5	5
Z6	5	3	3	4	7	2	8	3	4	7	8	5	5	8	8	5	6	1	7	4	4
Z7	7	2	1	6	2	6	6	4	5	5	1	6	1	4	7	7	8	3	4	7	4
Z8	1	5	8	1	5	4	4	8	3	3	6	3	2	2	5	6	7	2	2	8	6
Z9	6	8	1	2	6	2	8	5	6	7	5	5	3	8	7	2	8	8	7	7	4
Z10	3	6	6	8	4	1	8	1	8	6	4	7	6	6	1	3	3	4	8	6	8
Z11	8	8	1	2	6	3	8	5	6	1	2	5	3	8	7	8	8	8	1	7	4
Z12	3	6	6	8	4	1	8	1	8	6	4	7	6	6	1	3	3	4	8	6	1
Z13	6	8	5	5	6	7	1	5	6	4	5	5	8	1	2	4	5	6	5	2	4
Z14	3	6	6	8	4	1	8	1	8	6	4	7	6	6	1	3	3	4	8	6	8
Z15	6	8	5	5	6	7	1	5	6	4	5	5	8	1	2	4	5	6	5	2	4
Z16	3	6	6	8	4	1	8	1	8	6	4	7	6	6	1	3	3	4	8	6	8
Z17	1	5	8	1	5	4	4	8	3	3	6	4	2	5	5	6	7	6	2	8	7
Z18	6	7	4	2	8	5	8	5	6	7	5	5	4	8	4	2	1	8	6	1	2
Z29	3	2	3	2	4	6	7	5	2	1	6	2	6	1	5	2	5	4	2	6	2

Table 7.16: Clustering by P as a Response of Line Switching in the South Area part2

Clustering by P as a Response of Line Switching in the South Area part1

	L21 25B	**L22 23A**	**L22 23B**	**L22 25A**	**L22 25B**	**L23 24A**	**L23 24B**	**L23 29A**	**L23 29B**	**L24 25A**	**L24 25B**	**L24 28A**	**L24 28B**	**L25 26A**	**L25 26B**	**L26 27A**	**L26 27B**	**L27 28A**	**L27 28B**	**L28 29A**	**L28 29B**
K	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Z1	5	2	7	2	2	8	4	1	5	1	4	5	4	3	2	3	1	5	2	7	5
Z2	7	5	8	4	5	1	8	5	2	7	5	1	3	2	4	8	5	4	3	1	3
Z3	8	1	8	4	6	1	2	5	2	7	8	2	2	8	4	8	2	1	4	3	6
Z4	6	7	5	4	3	1	1	7	7	8	3	8	6	4	8	2	6	1	8	6	7
Z5	4	6	3	1	1	3	7	4	8	7	7	7	7	5	4	8	3	1	5	8	8
Z6	8	3	6	7	8	7	3	5	4	4	6	4	5	1	5	5	4	3	6	3	2
Z7	6	7	5	7	3	4	1	2	7	3	3	6	6	4	8	2	6	7	6	6	7
Z8	2	4	8	6	7	6	7	6	6	6	7	7	8	8	6	4	7	8	4	8	1
Z9	8	1	2	7	4	4	2	5	2	5	8	4	2	7	1	6	5	7	6	3	2
Z10	1	2	1	5	2	2	4	3	1	2	1	3	1	3	3	3	1	2	1	2	4
Z11	8	1	2	8	4	4	2	5	2	5	8	4	2	7	1	6	5	7	6	3	2
Z12	1	2	1	5	2	2	4	3	1	2	1	3	1	3	3	3	1	2	1	2	4
Z13	8	1	2	3	6	4	6	5	2	5	8	2	2	7	1	7	2	7	8	4	6
Z14	1	2	1	5	2	2	4	3	1	2	1	3	1	3	3	3	1	2	1	2	4
Z15	8	1	2	3	6	4	6	5	2	5	8	2	2	7	1	7	2	7	8	4	6
Z16	1	2	1	5	2	2	4	3	1	2	1	3	1	3	3	3	1	2	1	2	4
Z17	2	6	8	6	7	6	6	8	6	6	7	7	8	8	6	4	7	8	4	4	1
Z18	3	8	4	7	4	5	5	5	3	5	2	4	2	6	7	1	8	6	7	5	2
Z29	3	2	3	2	4	6	7	5	2	1	6	2	6	1	5	2	5	4	2	6	2

Table 7.17: Clustering by P as a Response of Load Increasing in the North Area

Clustering by P as a Response of Load Increasing in the North Area								
	L1	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**
K	5	5	6	5	5	5	6	6
Z9	5	4	4	2	5	3	5	6
Z10	4	1	3	1	2	2	1	4
Z11	5	4	4	2	5	3	5	6
Z12	5	5	4	1	2	2	1	4
Z13	5	3	6	5	1	3	4	2
Z14	5	5	4	1	2	2	1	4
Z15	5	3	6	5	1	3	4	2
Z16	5	5	4	1	2	2	1	4
Z17	1	2	5	4	5	3	5	5
Z18	3	1	3	2	3	4	3	3
Z19	5	4	1	2	4	3	5	6
Z20	1	2	5	2	5	5	5	6
Z21	2	4	2	4	5	3	6	5
Z22	4	1	3	1	2	2	1	4
Z23	4	1	3	1	2	2	1	4
Z24	2	1	2	1	2	2	1	4
Z25	4	1	3	1	2	2	1	4
Z26	2	4	2	3	5	1	2	1
Z27	4	1	3	1	2	2	1	4
Z28	4	1	3	1	2	2	1	4
Z29	2	4	2	3	5	1	2	1

Table 7.18: Clustering by P as a Response of Load Increasing in the Center Area

Clustering by P as a Response of Load Increasing in the Center Area										
	L9	**L10**	**L11**	**L12**	**L13**	**L14**	**L15**	**L16**	**L17**	**L18**
K	8	8	8	7	8	8	8	8	8	8
Z1	6	2	6	3	1	5	6	1	6	7
Z2	6	5	3	7	3	7	7	5	7	1
Z3	3	7	5	5	5	6	5	8	5	4
Z4	6	8	8	1	4	3	8	4	2	8
Z5	5	2	4	2	2	8	2	1	2	8
Z6	8	4	2	7	7	1	4	1	3	2
Z7	6	3	8	1	4	3	8	4	2	8
Z8	1	4	7	7	7	1	3	6	7	2
Z19	7	2	2	7	2	4	6	6	3	2
Z20	2	6	2	6	7	4	8	2	4	6
Z21	6	2	7	4	7	4	8	1	1	3
Z22	3	1	1	4	6	2	1	7	1	3
Z23	3	1	1	4	6	2	1	7	1	3
Z24	3	1	1	4	6	2	1	7	1	3
Z25	3	1	1	4	6	2	1	7	1	3
Z26	4	2	7	3	8	4	6	3	8	5
Z27	3	1	1	4	6	2	1	7	1	3
Z28	3	1	1	4	6	2	1	7	1	3
Z29	4	2	7	3	8	4	6	3	8	5

Table 7.19: Clustering by P as a Response of Load Increasing in the South Area

Clustering by P as a Response of Load Increasing in the South Area											
	L19	**L20**	**L21**	**L22**	**L23**	**L24**	**L25**	**L26**	**L27**	**L28**	**L29**
K	8	8	8	8	8	8	8	8	8	8	8
Z1	5	5	6	7	7	8	3	8	4	3	6
Z2	6	8	8	6	5	2	5	7	8	4	8
Z3	8	7	4	2	4	1	1	1	2	5	1
Z4	2	1	7	3	2	6	7	4	7	1	4
Z5	7	5	8	1	3	4	4	5	6	6	7
Z6	4	6	1	1	8	3	2	2	1	8	6
Z7	2	1	7	3	2	6	7	4	3	1	3
Z8	7	2	8	4	8	3	6	7	6	3	5
Z9	7	5	8	1	8	2	5	5	6	2	6
Z10	1	4	4	5	1	5	1	6	2	7	1
Z11	7	5	5	1	8	2	5	5	6	2	6
Z12	1	4	5	5	1	5	1	6	2	7	1
Z13	3	3	2	8	8	2	8	5	5	2	2
Z14	1	4	4	5	1	5	1	6	2	7	1
Z15	3	3	2	8	8	2	8	5	5	2	2
Z16	1	4	5	5	1	5	1	6	2	7	1
Z17	7	2	8	4	8	3	6	7	6	3	5
Z18	7	5	3	1	6	7	5	3	6	3	6