

ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA

ARCES - ADVANCED RESEARCH CENTER ON ELECTRONIC SYSTEMS

---

# Vulnerability and robustness indices against blackouts in power grids

**Carlos Manuel Formigli**

SUPERVISORS

Professor Riccardo Rovatti

Professor Gianluca Setti

COORDINATOR

Professor Claudio Fiegna

---

DOCTORATE ON INFORMATION TECHNOLOGIES

JANUARY 2011 - DECEMBER 2013

XXVI CYCLE - ING-INF/01 - 09/E3

FINAL EXAM 2014





---

# Dedication and Acknowledgments

**T**HIS work is dedicated to the Universities of Tucumán and Bologna, beloved institutions.

I would like to profoundly thank all the people working at ARCES, especially to my supervisors, Riccardo Rovatti and Gianluca Setti, who taught me some important things about researching.

To the entire European Community, represented by the European Commission who has provided the economic means to develop this thesis. To my colleagues and friends in the "open space": Valerio Cambareri, Salvatore Caporale, Mauro Mangia, Fabio Pareschi and also to Sergio Callegari, Javier Haboba, and Fernando Luna. I learned things from each one of them: sometimes, a way for doing something; sometimes, a way of being "more italian". To my friends who, although being far away, always were truly close companions: ¡Gracias Ana María, Guillermo, Verónica y Alejandra!



---



# Abstract

**I**N this dissertation some novel indices for vulnerability and robustness assessment of power grids are presented. Such indices are mainly defined from the structure of transmission power grids, and with the aim of Blackout (BO) prevention and mitigation. Numerical experiments showing how they could be used alone or in coordination with pre-existing ones to reduce the effects of BOs are discussed.

These indices are introduced inside 3 different subjects:

The first subject is for taking a look into economical aspects of grids' operation and their effects in BO propagation. Basically, simulations support that: the determination to operate the grid in the most profitable way could produce an increase in the size or frequency of BOs. Conversely, some uneconomical ways of supplying energy are shown to be less affected by BO phenomena.

In the second subject new topological indices are

devised to address the question of "which are the best buses to place distributed generation?".

The combined use of two indices, is shown as a promising alternative for extracting grid's significant features regarding robustness against BOs and distributed generation. For this purpose, a new index based on outage shift factors is used along with a previously defined electric centrality index.

The third subject is on Static Robustness Analysis of electric networks, from a purely structural point of view. A pair of existing topological indices, (namely degree index and clustering coefficient), are combined to show how degradation of the network structure can be accelerated.

Blackout simulations were carried out using the DC Power Flow Method and models of transmission networks from the USA and Europe.

## **Dissertation Outline**

In chapter 1, a description of power grids structure, components and functioning is done, as well as some explanation regarding their historical development, and the BO problem. Models, and computational techniques to simulate grid operation are commented.

In chapter 2, the problem of BO is addressed in more detail, mentioning its causes and dynamics. Also, various approaches to take rid of them are commented.

In chapter 3, a handful of indices and parameters used in grid security assessment are reviewed, especially in connection with BO evaluation and prevention. Some comments on their strengths and weakness are done.

In chapter 4, Novel indices and ideas for BO reduction are introduced, commenting motivations and expectations considered for the corresponding definitions. Details of models and simulations are explained.

Chapter 5 presents final comments for this thesis, including discussions regarding the novel indices developed, mentioning applicability, enhancements and possible modifications.





---

# Contents

<b>Dedication and Acknowledgments</b>	<b>i</b>
<b>Abstract</b>	<b>iii</b>
Dissertation Outline . . . . .	iv
<b>1 Introduction</b>	<b>1</b>
1.1 Power Grids . . . . .	4
1.2 The Problem of Blackouts . . . . .	12
1.3 Modeling Techniques in Power Grids . . . . .	16
<b>2 Power Grid Security and BO Mitigation Tech-     niques</b>	<b>27</b>
2.1 Generation and load Modifications . . . . .	29
2.2 On-line and off-line BO foreseeing . . . . .	33
2.3 Contingency Analysis (CA) . . . . .	34
2.4 Successful methods? . . . . .	35
<b>3 Security, robustness, reliability indices and     parameters</b>	<b>37</b>

3.1	Structural or Topological Indices . . . . .	38
3.2	Indices for BO assessment . . . . .	43
<b>4</b>	<b>ORIGINAL INDICES</b>	<b>45</b>
4.1	Economical Dispatch and BOs . . . . .	45
4.2	Distributed Generation and BOs . . . . .	59
4.3	Combined Indices for Static Contingency Analysis . . . . .	73
<b>5</b>	<b>Discussion and Conclusions</b>	<b>85</b>
5.1	On stress and dispatch policies . . . . .	85
5.2	On OSF index . . . . .	86
5.3	On combination of indices for Static Robust- ness Analysis . . . . .	87
5.4	Original Contribution . . . . .	87
	<b>Bibliography</b>	<b>89</b>
<b>A</b>	<b>Details of Power Flow Methods</b>	<b>99</b>
A.1	Gauss-Seidel method . . . . .	100
A.2	Newton-Raphson Method . . . . .	100
A.3	Decoupled Power Flow . . . . .	104

# 1 Introduction

Power grids are technological structures of major importance for modern society, providing a mean for transportation of generated electrical energy towards consumers. Since the time of first installed power grids, sporadic failures has been observed in an almost random pattern, leading to partial or complete lost of service to consumers. Such malfunctioning conditions, along with recovering time and economic losses was baptized generically with the name Blackout (BO). With the passing of time, power grids have evolved, increasing supplying capacity, geographical extension and complexity, and BOs went from simple and tiny inconveniences towards the emergence of extensive cascading phenomenon. Sometimes such BOs reach very considerable size, having the property of being unpredictable, even if a considerable number of techniques and procedures have been devised with the aim of mitigating their effects. Also, a number of indices and indicators for security and grid state assess-

ment exist, each one more or less appropriate depending the network under consideration, and showing variable effectiveness. Different approaches to reduce BOs risk are used, but in general no one is the definitive solution. The quantity of proposed techniques is enormous, but as economical consideration are to be taken into account when talking about BO prevention and mitigation, just a little portion of the total proposals are implemented in practice. No technique is "free", and the gap between theoretical correction and technical possibilities of implementation could have a prohibitive cost. From an engineering point of view, the main goal is to arrive at practical but not expensive solutions, since power grids are technological machinery with the clear economical purpose of transporting and selling energy. Besides that, it is understood that theoretical developments to explain and bound BO and cascading phenomenon are still necessary [1].

Despite the efforts in reducing BO size and occurrence, they are still a real somehow random problem, growing more or less at the rate of growing of grids. A simple extrapolation, would indicate that the future size of this failures will make the problem at hand a real nightmare if reliability of service is to be guaranteed to the costumers. According to some researchers (e.g. [2]), the problem could be even worse since the generalized lack of new transmission lines and increment in transmission capacity makes overloading a state more common to the everyday functioning of grids. Also the very structure of the grid is evolving in various ways. Not only the technological advance in the major components is modifying constantly the visible face of the machine; the functioning and

coordination of all the parts is also having a strong variation due to many causes, like for example:

- The desire of more automation, and realization of smart grids.
- The communication structures to maintain the grid working as a whole or to form, if desired, islands.
- The changing governmental rules to regulate and promote the liberalization of the energy market, introducing more and more stakeholders.
- The need to adapt grid operation procedures to those changing legislations.
- The need to make space for the insertion of new energy sources, and . . .
- The raising introduction of distributed generation.

All this forces of change should have with no doubt an effect on BO occurrence, and so, research on this topic is well justified. As said before, theoretical research for enhancing grid performance and reliability is being done, and numerous merit figures and indices have been yet developed. But, as final assessment and implementation of new techniques is not an easy task, or even too expensive, new ideas are always welcome.

Considering the relative delay in the construction of new transmission lines to meet demand, or at least to match the growing generation capacity [2], more research regarding the fragility, or robustness, of the transmission networks from a structural point of view is reasonable. Besides this, the increasing addition of distributed generation (which normally have natural constraints regarding

duty cycle but less problems to modify its geographical location) brings to the discussion the question of where to insert such generation units. Variations in the general state of the grid's load caused by new DG shall also influence the occurrence of BOs. Therefore, trying to discover and define technically objective figures of merit and indices for the inclusion of DG, is also a matter of interest, [3].

## **1.1 Power Grids**

### **1.1.1 Mission and historical development**

An electric power grid is the entire apparatus of wires and machines that connects sources of electricity with customers and their multiple needs [4]. From a historical perspective, the electric power system evolved in the first half of the 20th century without a clear awareness and analysis of the system-wide implications of its evolution. The role of electric power has grown steadily in both scope and importance during this time, and electricity is increasingly recognized as a key to societal progress throughout the world, driving economic prosperity and security and improving the quality of life. For example, in the United States in 1940, 10% of the energy consumption was in form of electricity; as time passed by the portion of electricity vs. total energy consumed has risen up to 40 % nowadays. Electric grid now underlies every aspect of our economy and society, and it have been considered among the engineering innovation most beneficial to our civilization. .

In the early days of power systems, generation and

transportation of energy was done mainly in DC, being AC systems of less extension. After a pair of decades of development and discussion, AC generation and transport conquer almost the totality of the market and infrastructures due to its easy conversion to different voltage levels, up and down, allowing relatively simple devices to manage HV- low current from transmission lines, to supply low voltage- moderate current for final users. DC systems was reduced for almost a century to interconnecting links between major AC systems, or for relatively small and isolated regions. Such dispute between DC and AC was resolved and implemented by conventions based on practical convenience and technological limitations, and although DC generation is starting to gain interest because of the primordial DC power consumption of electronics devices, the supremacy of AC is to be kept still for a while.

With a rough similarity to the AC-DC evolution, another trend involving power generation is happening now. This time, the main character is power generation and its connection to consumers. Disregarding whether the generation was DC or AC, each one of the first systems was always strongly related with a primal consumer. That is: each generator was meant to serve a specific center of consumption or population and, in principle, that consumer was in the generator's neighborhood. The next step in grid's growing came from the increasing size of consumption and the settling of power plants in appropriate but distant places. So, at that point the use of medium-big longitude lines to connect generator and consumers give the real born to the grid. Interconnections between different consumers and generators to provide alternative

and backup paths to energy transportation conclude the basic structure of electric grid as we know today. In this, now mature scheme, most of generation is composed by facilities of high size and normally geographically far from consumers; this is called Concentrated Generation (CG), different of what was used in the early times of grids.

Power grids are still meanly composed of transmission lines and concentrated generation centers, like hydro, nuclear, coal, or fuel devices, more or less far from the consumer points. This archetype, has lasted for almost a century. Nowadays, the general grid's scheme is returning in some sense to the original settlement of generator not so far away from consumers due to the arrival and progressive introduction of renewal power sources, characterized by having low to medium size compared to concentrated centers. More importantly, this type of power generation is normally in close vicinity with consumers and normally have a lack of capability to deliver power at a constant rate for a long period or, at any hour of the day. This type of generation is basically called Distributed Generation (DG). Even though there are many definitions for it, depending on local regulations of each country, this is roughly constituted by generation units of limited size (around 10 MW or less) interconnected at the substation, distribution feeder or customer load levels [5], and often of private property [6]. DG technologies include photovoltaics, wind turbines, fuel cells, small and micro sized turbine packages, Stirling-engine based generators, and internal combustion engine-generators. Actual DG is strongly related with green power sources, and sometimes confused with them. Power grids are changing in an accelerate way, due to the insertion of DG, and the

possibility of degradation in power quality, reliability, and control due to this insertion should be minimized, [3].

The addition of new generation technologies, structural change involving operation, the establishment of deregulation of electricity markets and the consequent need to adapt the operation to the legal constraints, and the struggle to make electrical systems increasingly independent of human errors, results in the need for a relatively profound change in the way the network coordinate their operation. It is expected that these machines get sufficient "intelligence" to handle all the many variables involved, reaching a stable and economically convenient operation, as automatically as possible. The latter because it is becoming increasingly clear that the operation of the networks is somewhat restricted by the limited number of variables that human operators can manage, characterized by the ever present possibility of accidental mistakes. The new paradigm in relation to the intelligent operation of grids and its ability to adapt itself to variable conditions has been coined as "Smart Grid".

Again, there are many definitions of this concept, among which it is worth mentioning the following, which cover most features to consider: "The Smart Grid can be defined as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across the entire spectrum of the energy system from the generation to the end points of consumption of the electricity", [7]. "Smart grid is envisioned to improve efficiency, reliability, and flexibility of the current grid while reducing the rate at which additional electric utility infrastructure needs to be built", [8].

It is expected that the grid should be smart enough to avoid as much as possible BOs, or otherwise recover promptly after such events. Anyway, BO prevention methods previously designed need to be modified or tuned up for a better match with the new energy policies and technologies.

### **1.1.2 Grid's Components**

The electrical power system consists basically of the following three parties:

- Consumers, who pay for energy to be used in lighting, building conditioning, motors, industrial processes, etc. Represent the loads.
- Energy sources, in the form of power plants, of various types, sizes and fuels.
- Delivery system, whereby electric power is transported from the generators to the customers along transmission lines. Without this lines the "grid" would be inexistent.

Excluding the customers and their appliances, power grids have a big variety of components. Those can be seen at its time as belonging to one of three groups, namely:

- i. Active elements for power generation and transformation;
- ii. Maneuver elements, that makes possible the interconnection of other elements as well as the ability of changing grid's structure in order to redirect energy through not overloaded lines, and...

- iii. Protection elements, aimed to prevent overloading and destruction of power handling elements.

Also, measuring and communication devices are indispensable for grid operation, even if they are not directly implied in power handling. For example, for flow calculation and estimation these devices do not normally require explicit modeling, being somehow transparent from a theoretical point of view. But in real life, these devices can be target of malicious attacks almost as harmful as direct destruction of power handling components. Additionally, human beings, since their expertise can produce significant different results in case of emergency, could also be still considered as grid components, [1].

### **1.1.3 Transmission and Distribution Systems**

Electric grids have grown so as to have an intricate layout. However since the goal of the network is the transmission of energy from generating facilities to centers of consumption, it is possible to distinguish two types of meshes formed by the supply lines. The first group corresponds to transmission networks that connect consumers and (rather distant) generators; they work with the higher voltages available and, have truly web structures. In the second group are distribution networks, formed by lines inside the population centers, connecting directly to residential, commercial and industrial users. These networks use lower voltages, from a few tens of kV, to a minimum of 110 or 220 Volts. The major difference between the two types of networks is in their topologic

structure: distribution networks are almost always of radial, and sometimes of loop shape; being the web structure a quality of transmission networks. Distribution networks have one, or few points for bulk energy input, being the very first lines going out from the transforming substation called as "feeders". From these points, low voltage lines branch into a tree. Additionally, DG is placed inside distribution networks, on branches of the structure. Another minor difference is that distribution lines are increasingly of underground type, while transmission lines are mostly of the overhead type.

Regarding operation, these two types of networks have several differences. Distribution networks show more variability in their structure, as consumer demands and location within the area belonging to each "feeder" are constantly changing, and then switching devices are operated to adjust voltage levels and choose the best routes for energy. Transmission networks are comparatively more stable in their structure. Differences in operation due to variability in structure and loads concentration, lead to the fact that control algorithms, security provisions and indices, etc. are also different for one type of network or the other one. This helps in understanding that since its beginning "smart grids" development was focused on the management of distribution networks; whereas today, the challenge of making the Smart Grid a reality is somehow the challenge to achieve an efficient and reliable coordination between transmission and distributions systems.

### 1.1.4 Present Changes and Trends

Up to not so long ago, network power flow were mainly dominated by the production of concentrated generators, being DG of supposedly minor relevance in what transmission power regards. But nowadays, the ascending share of power delivered by distributed generators is becoming of importance from the point of view of transmission, since the modification on the power required by a feeder may be appreciably modified by total variations of DG power in a zone, [9]. Such influence is translated in relatively strong variations in transmission lines power flow, bringing the possibility of unexpected overloading on those lines. In the history of power energy development it was ever observed as matter of fact that any modification to the system could produce an undesirable collateral effect. It is likely applicable also to the gradual increase of DG penetration, which involves in principle more security, reliability and resilience for the grid; but as suggested in [9] some combinations of DG with CG have potential for decreasing the grid's performance against BO.

Stress on the current grid is expected to grow in the short term due to lack of investment in new transmission lines [2]. This is somehow a result of deregulation of the electricity market, and the subsequent appearance on the scene of energy and transportation providers in mutual competition. It happens that the flow of energy through the parts of the network is not subject to human decision but to the laws of physics; and the construction of a new transmission line is not just for the benefit of the builder but also for all other networked stakeholders. These two facts produce strong reduction of investment desire

from competing parties in the electric market. Hence, the relative lack of investment together with the constant increment of consumption of about 2.4% annually [10], suggest that the risk of BO will arise either due to the size and frequency of the events.

## 1.2 The Problem of Blackouts

BO in power grids are big disturbances, generally occurring in seasons of high energy consume, and rush hours. May be, the most distinctive characteristics of BO are not its sizes but, their unpredictable nature and their progressive, fast, and difficult to stop growth. An isolated initial failure or malfunctioning equipment serves as trigger to change others network components loading state, which at their times also succumbs by overloading, protection device improper triggering or sometimes a total component destruction. A remarkable property of grids with reference to BO is that as time went by even if a rather big number of techniques have been developed for preventing those failures, BO are still happening at a sustained rate. Numerous revisions of historical data and reports of blackouts, suggest that their number and size is increasing, [11], [12].

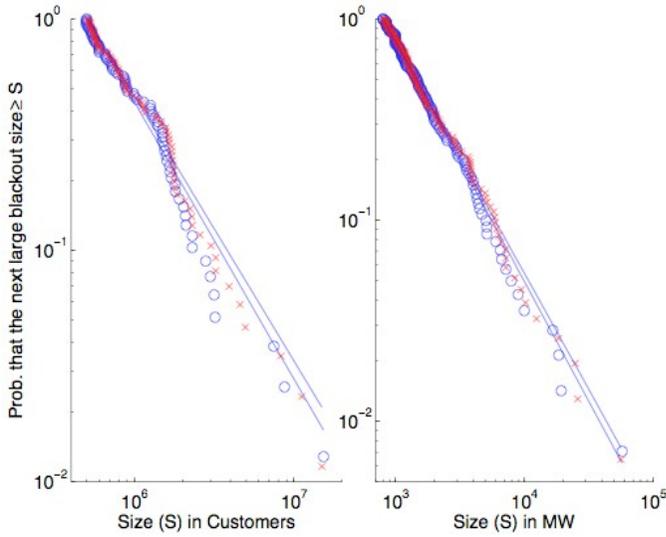
From a technical standpoint BO are difficult to treat due to the complexity of the power grid. This complexity of the electrical system leads to many of its features, and the phenomena produced are qualitatively similar to those observed in other complex systems, either artificial or natural. Some examples of such systems are: the www, networks of biochemical interactions, interactions

between species. The phenomenon of BOs is usually compared to epidemics, both in the way it can start and develop and in the frequency and size of events. Also, occurrence and sizes of BO driven in an especial way by the increasing demand, give clues to categorize active power grids as critically self-organized system, [13], [14]. In this regard, the influence of grid's structure is easy to suppose as very important, as has been indicated for example in [15], [16], [17].

Cumulative probability distributions of BO's sizes on grids all around the world fits well with power laws. This is considered as an indication of the complex nature of the phenomena involved in the occurrence of BOs, [16], [18].

In figure 1.1 probability distributions of BO's sizes and affected customers in USA for a time period of about 20 years is reproduced from [19], showing the aforementioned fit to power laws.

Each BO produces many inconveniences to people affected, but especially in form of direct and indirect economic losses, often substantial, mainly from the productive activities that are forced to stop due to lack of energy. Breakage of some consumer-owned machines also often do occur. The impact of a Blackout is greater the longer it takes to restore energy supply, in a more than linear fashion, being able to produce lack of water and fuel provision, and the spread of diseases and vandalism, [1], [19]. The BOs are capable of producing similar damage to major natural disasters such as earthquakes and hurricanes having a profound effect on the lives of people. It has been said [2] that BOs can be viewed "as a disruption of social experience, as a military tactic, as a crisis in the networked city, ... as the outcome of



**Figure 1.1:** The cumulative probability distribution of blackout sizes in customers (left, for events  $\geq 500$ k customers) and MW (right, for events  $\geq 800$  MW). X marks indicate blackout sizes adjusted for population/demand growth. O marks indicate un-scaled data. The lines show the power-law fit to the data. (Extracted from [19]).

inconsistent political and economic decisions, and more". BO are complex phenomena, and fighting them is not an easy task; there is evidence of raise in size of big BO as a consequence of prevention techniques designed to manage little disturbances, [18].

### 1.2.1 BO Dynamics

As said above, BO happens normally in moments of high consume, although being able to materialize without any prerequisite. What is a constant behavior during a BO, is the turning off of grid component, and the consequent migration of power flow towards other zones of the grid,

bringing to them additional threat of overloading.

While the failure of a single network element can trigger a cascade of other elements, this situation rarely occurs, due to security measures taken for the proper functioning of the network [27]. One of such security measures is called  $N - 1$  security rule, (see section 2.3), which impose that the network must be able to withstand the failure of any single element (generator, transformer, transmission line) while avoiding the overloading of any of the other elements of the network beyond its capacity. This is why, in reality, most frequent BO start due to two or more concurrent component faults.

After an initial event, (failure of one or more components at the same time) two different things can happen to the power flow in the grid:

- i. A steady-state progression, which is a slow succession of faults (overloading of line, transformers, generators)
- ii. Transient Progression, in fast succession: large components going out of order due to under voltage or under frequency conditions. The component start a quick disconnection and, uncontrolled isolation of important areas do occur feeding the BO.

It is assumed that BO progression could be stopped in the stage of steady-state progression since time to take corrective actions normally is sufficient enough; whereas the possibilities of stopping a cascade failure during a transient is strongly limited. Although this two processes seem to be well differentiated, the more likely situation is a superposition or alternation of both during a real BO.

The location of the first (or compound) failure is unpredictable, and its cause can come from many sources.

The subsequent elements going off are in principle predictable using as a starting point the new loading state of the grid, but there is also a stochastic ingredient in the real outcome of a BO, due to the not total knowledge of such state, measurement errors, and hidden failures in protecting equipment, [1].

Something very important to notice is the fact that cascading failures and BO are a side effects of the existing protection strategy [11]. This strategy is to de-energize (switch off) each and every device that develops overstress, such as exceedingly high or low currents or voltages. A disturbance, such as a short circuit, often produces overstress in the devices close to the disturbance. De-energizing these devices eliminates these overstress, but sometimes, the de-energizations produce overstress in other parts of the network.

### **1.3 Modeling Techniques in Power Grids**

A key characteristic in grid's power flow is the balance between generated and consumed energy, but determining power flows on each line is not so simple to do. Additionally, all currents and power flows should be below the maximum capacities of the components, observing acceptable margins for the sake of security and stability of operation. No need to justify that knowing the grid's loading state is essential to control the system. As in all other branches of technology, modeling real systems

to explore its capabilities through computer simulations is also a common practice for power networks. Suitable models use and simulation can reveal features of systems operation before construction or field test of new ideas. In the case of power grids, it also serves to assist in the determination of the sequence of events which could have produced a BO. Calculation of loading state of major elements in a grid is intensively used to identify, in advance, risky situations in case of some selected possible failures; or to determine the effect of a control action before its implementation on the hardware. As for all physical systems, for networks there is not a perfect model nor is there a unique way to do it. This happens for several reasons, among which it is always present the limited accuracy of measurements, and in the case of networks there is additionally its strong complexity. Detailed information of the huge number of devices is never available. Thus, a significant degree of inaccuracy exists whenever simulated values and measured ones are compared for a real network.

In the next sections the most common models and methods for calculating grid state are gazed, and the one chosen to use in this thesis is discussed in more detail.

### **1.3.1 Graphs**

To represent the structure of power grids, one of the most used tools are undirected graphs, sometimes weighted and sometimes unweighted. The buses and lines of the grid, are the nodes and edges of the graph respectively. The quality of "undirected" is for taking account of the capability of power flow to come and go in both directions

along lines. Unweighted graphs are useful when only the connections between buses and lines are to be represented; and weighted graphs are used when also the impedance of lines is desired to take part into calculations. Graphs are summarily useful to represent the connections of networks as specific data structures, facilitating search and ordering of components, paths between them, and the calculation of many indices and figures of merit.

### **1.3.2 Power grids from the point of view of complex systems**

Although the study of power grids could seem to be just a matter of modeling an equivalent network, the size of real grids aside the variety of different components interacting and, the inexact knowledge of their states, lead to the inability to control such systems as desired. Nonlinear effects and strong enough stochastic changes are always present and despite the technical efforts for simplifying the operation of grids, these technological structures manifest their quality of being very complex systems.

Power grids have been explored in that frame, and compared with other complex systems either real or theoretical on the search for clues to understand in a better way the phenomena developed inside them [21], [22], [23], [24], [17]. This type of research concentrates mostly on qualitative aspects, both of system constitution and functioning, since detailed quantitative knowledge of individual components is not accessible.

Some of the properties that are considered important in the field of complex networks are for example: the growth of the system itself; the spread of information

or other flow through the network; where do bottlenecks occur?, and what are its effects?; when do critical conditions happen before rupture or avalanches?; how does network disintegration happen?. Talking about power grids, this would correspond to the phenomena of cascading failures and BO; island formation; and when do network saturation occur?.

### 1.3.3 Electric Grid, and Power Flow Calculation Models

Flow of power in each network element is the most important aspect of what is called "the state" of the grid. So, various method for calculation and approximation of power flow have been developed.

The most important variables to be calculated in power grids, are those for any electric AC circuit: voltage and phase at each node, and currents flowing through lines (branches). As input data, what is required is the structure of the grid, the power supplied or consumed in each node, and the impedances connected between nodes, that is: the line impedances through which electricity is delivered; and additionally, the impedances from each node to ground.

Basic definition of variables for considering buses, lines and other devices of the grid are needed by power flow calculation methods. Here such considerations are: In each grid there are  $N$  nodes. The  $i$ -th node ( $i = 1, \dots, N$ ) is characterized en general by a power  $P_i$ . Also each node has a voltage magnitude  $|E_i|$  and phase  $\Theta_i$ . Between nodes we have  $K$  transmission lines. The  $k$ -th ( $k = 1, 2, \dots, K$ )

line transfers power from its two connecting buses, which can be nominated  $a(k)$  and  $b(k)$  with  $a(k) \neq b(k) = 1, \dots, N$ .

The most common methods for power flow calculation are Gauss-Seidel, Newton-Raphson, Decoupled and, DC; being this last one the used thoroughly in this thesis. Major characteristics of mentioned method are explained in the following sections, (also in [46] and appendix A).

### **The Gauss-Seidel power flow method**

In this method the voltages at each bus,  $E_i$  can be solved iteratively starting from an initial guess. The iteration equation in this case is of the form:

$E_i^{n+1} = F1(E_y^{n+1}) + F2(E_z^n)$ , with  $i \in [1, N]$ , including all nodes with  $y < i$  and  $z > i$ .

$F1$  and  $F2$  are multivariable functions having as arguments the voltages on every bus. (Details of  $F1$  and  $F2$  expressions can be found in appendix A and in [46]). The Gauss-Seidel method was the first AC power-flow method developed for solution on digital computers. This method is characteristically long in solving due to its slow convergence and, often difficulty is experienced with unusual network conditions such as negative reactance branches. Iterations are executed until the difference  $E_i^{n+1} - E_i^n$  is below an specified value or the number of iterations exceeds a maximum.

One of the disadvantages of the Gauss-Seidel method lies in the fact that each bus is treated independently. Each correction to one bus requires subsequent correction to all the buses to which it is connected. The next methods have better performance in this regard.

### The Newton-Raphson method

The Newton-Raphson method is based on the idea of calculating the corrections of each  $E_i$  while taking account of all the interactions. The voltages of nodes are considered in polar coordinates, producing two sets of expressions, namely one for  $|E_i|$  and another for  $\Theta_i$ . As Gauss-Seidel does, Newton-Raphson method starts from an initial guess of  $|E_i|$  and  $\Theta_i$  and seek for the approximate amount ( $\Delta|E_i|$  and  $\Delta\Theta_i$ ) to correct the initial values. This is done using the function relating power at nodes ( $P_i + jQ_i$ ) with voltages and phases ( $|E_i|$ ,  $\Theta_i$ ), and the Jacobian of such function. (Derivation of the Jacobian can be seen on appendix A).

The important expressions used for iteration are:

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} = [J] \begin{bmatrix} \Delta \Theta_1 \\ \frac{\Delta|E_1|}{|E_1|} \\ \Delta \Theta_2 \\ \frac{\Delta|E_2|}{|E_2|} \\ \vdots \end{bmatrix} \quad (1.1)$$

also...

$$\begin{bmatrix} \Delta \Theta_1 \\ \frac{\Delta|E_1|}{|E_1|} \\ \Delta \Theta_2 \\ \frac{\Delta|E_2|}{|E_2|} \\ \vdots \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} \quad (1.2)$$

using this last one (1.2), the values of  $|E|$  and  $\Theta$  are updated after each iteration until difference with respect to the previous estimation is below an specified value, or the number of iterations exceeds a maximum. Solving for  $\Delta\Theta$  and  $\Delta|E|$  requires the solution of a set of

linear equations whose coefficients make up the Jacobian matrix, The Jacobian matrix must be also recalculated at each iteration, but generally it has only a few percent of its entries that are nonzero. So programs that solve an AC power flow using the Newton-Raphson method are successful because they take advantage of the Jacobian's "sparsity". The solution procedure uses Gaussian elimination on the Jacobian matrix and does not calculate  $J^{-1}$  explicitly.

Convergence of Newton-Raphson method is quadratic, well better than the corresponding to Gauss-Seidel. Newton-Raphson method is called "full Newton" power flow method, since produces the most accurate results. Also, the robustness of its convergence is better than in other iterative methods.

### **The Decoupled method**

The Newton-Raphson method is the most robust power flow algorithm used in practice. However, one drawback to its use is the fact that the terms in the Jacobian matrix must be recalculated each iteration, and then the entire set of linear equations must also be resolved each iteration. Since thousands of complete power flows are often run for a planning or operations study, ways to speed up this process were sought. Decoupled method consist in a simplification of the Newton-Raphson method in order to avoid the burden of solving and inverting the Jacobian matrix at each iteration. Among others (derived as explained in appendix A), the most important simplifications are:

Let  $\cos(\Theta_i - \Theta_k) \approx 1$ .

Assume  $r_{ik} \ll x_{ik}$ .

Such simplifications lead to two set of equations, in which the matrices  $B'$  and  $B''$  are constant, and therefore diminish the total computational burden:

$$\begin{bmatrix} \frac{\Delta P_1}{|E_1|} \\ \frac{\Delta P_2}{|E_2|} \\ \vdots \end{bmatrix} = [B'] \begin{bmatrix} \Delta \Theta_1 \\ \Delta \Theta_2 \\ \vdots \end{bmatrix} \quad \text{and,} \quad \begin{bmatrix} \frac{\Delta Q_1}{|E_1|} \\ \frac{\Delta Q_2}{|E_2|} \\ \vdots \end{bmatrix} = [B''] \begin{bmatrix} \Delta E_1 \\ \Delta E_2 \\ \vdots \end{bmatrix} \quad (1.3)$$

These two expression are solved iteratively, but contrary to Newton-Raphson method, each set of variables is updated independently from the other one.

### DC power flow

This is the method used in chapter 4. A further simplification of the decoupled power flow algorithm can be done simply dropping the Q-V equation (in 1.3) altogether. This results in a completely linear, non-iterative, power flow algorithm. To carry this out, we simply assume that all  $|E_i| = 1.0$  per unit. Then eq. 1.3 becomes:

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \end{bmatrix} = [B'] \begin{bmatrix} \Delta \Theta_1 \\ \Delta \Theta_2 \\ \vdots \end{bmatrix} \quad (1.4)$$

The DC power flow is only good for calculating MW flows on transmission lines and transformers. It gives no indication of what happens to voltage magnitudes, or MVAR or MVA flows. The power flowing on each line using the DC power flow is then:

$$P_{ik} = \frac{1}{x_{ik}} (\Theta_i - \Theta_k)$$

Next, some details used here for the construction of expression 1.4 and in simulations of chapter 4.

Additionally to the generic power  $P_i$  present on each bus, in this thesis it has been useful making a distinction among buses with power supplies and buses acting as loads: these powers were nominated as  $G_i$ , and by  $L_i$  respectively. Nodes are such that  $G_i L_i = 0$  for any  $i = 1, \dots, N$  so that we may distinguish  $I$  input nodes that are generators since  $G_i > 0$  and  $L_i = 0$ ,  $J$  load nodes such that  $G_i = 0$  and  $L_i > 0$ , and  $T = N - I - J$  transmission nodes in which  $G_i = L_i = 0$ .

Each line has a series resistance  $R_k$  and a series reactance  $X_k$ , for which we assume  $X_k \gg R_k$  so that the latter can be neglected.

Phase difference between nodes are supposed small enough in order to maintain steady state stability; this allows the approximation of sine function of angles by their argument. Each line is also characterized by a flow capacity, that in terms of voltage stability can be considered around  $C_k < \frac{1}{2X_k}$  [25]. All variables are expressed in the per unit system (P.U. system), and so can be managed as dimensionless quantities.

By defining an  $N$ -dimensional net power vector  $P$  with entries  $P_i = G_i - L_i$  for  $i = 1, \dots, N$ , an  $N$ -dimensional vector  $\Theta$  whose  $i$ -th entry is the phase at the  $i$ -th node and the  $N \times N$  matrix  $Y$  containing the imaginary part of the admittance matrix of grid's equivalent circuit we have:

Something to notice is that the set of  $N$  equations is redundant leading to a singular system. The entries of  $P$  sum up to zero and the phases are relative quantities; hence, it is common to set, for example,  $\Theta_N = 0$  and discard the last entry of  $P$  to obtain an invertible linear relationship between the vector of net power and the phases. In this way node  $N$  is taken as reference (or slack

node), and phases and powers of the remainder nodes are linearly related by an invertible matrix, as expressed by 1.4

$$P = Y\Theta \quad (1.5)$$

(Matrix  $Y$  basically contains the same information as  $B'$  in equation 1.4) If bus power are known, node phases calculation can be done by inversion of equation 1.5:

$$\Theta = Y^{-1}P \quad (1.6)$$

Power  $F_k$  flowing through the  $k$ -th line depends on line impedance and relative phase between nodes:

$$F_k = (\Theta_{a(k)} - \Theta_{b(k)}) / X_k$$

This relation can be expressed in matrix form, since phases can be sought as linear combinations of bus powers, according to the relation 1.6. Such linear relation could be expressed as in equation 1.7:

$$F = MP \quad (1.7)$$

This last one is intensively used in chapter 4, due to its easy to insertion in linear programming problem solutions. Something interesting to note is that  $M = \{H\}$  is the matrix of shift factors (called also power transfer distribution factors) referred to the slack bus of the network. (Shift factors are used in section 4.2.6).



## 2 Power Grid Security and BO Mitigation Techniques

**I**N this chapter the most common causes of BO are discussed, and some the techniques and control actions used to reduce their number or their effects are revised. Interest in this thesis focuses on the transmission networks, so overloads and breaks in lines are major faults which will be discussed hereafter. Failures in generators or transformers are taken into consideration through its equivalent effect on the total power supplied to the corresponding node of the network.

As said before, a BO can start from a sudden or slow change in loading state, which could lead to the triggering of protection elements or, start from an isolate component's failure. Destruction of active components can be produced by meteorological phenomenon, or mere malfunctioning of protection elements. Also failures or destruction can be produced by intentional attacks, a possibility that has produced generalized worry in last years.

BO propagates over a network putting out of order its components, either by the triggering of protection elements or by simple destruction of the less fortunate ones. In almost all cases the propagation is mainly due to protection relay action, responding to local overloading conditions. Cascading failures and BO are a side effects of the existing protection strategy [11].

In the search of BO prevention and mitigation, actions normally concentrates in the appropriate disconnection of components in order to decrease overloading, even if some consumers have to be leaved without service. So BO prevention techniques work mainly to operate properly maneuver elements and modify the power delivery scheduling, and loading. It is increasingly difficult to make the grid full time safe, because insertion and removal of generation and loading conditions do not last for more than 1 hour in a year [25]. Additionally growing of the grid also increase its loading state variability. Disconnecting nodes and lines after the initial failure can reduce the spread of blackouts [26], but as a collateral effect, in some cases, fighting small blackouts can increment the likelihood of larger blackouts [18].

The benefits of each Bo fighting technique is not easy to evaluate. This difficulty in assessing such preventing techniques comes from the fact that a technical field test is impossible from a practical standpoint. Even considering the margin of error in the values of the involved analogue variables, each state of loading lasts for a little time, and is basically not repeated again, due to the large number of elements involved.

Besides this, there exist the additional difficulty of the time scale in which real BO occur. This leads again to

the conclusion that almost the only reasonable way of research against the BO problem is through computer simulations.

Another alternative is to use information of past blackouts, to inquire into the causes and development thereof. One approach is trying to find statistically what of the grid's states bring out the strengths or weaknesses of the system. Again in this approach, there is always the problem of lack of data, since monitoring and recording all desired variables it is not possible. The sequence in which past events occurred is often unknown until the information from various sources is contrasted, (each different area operator must provide data coming from his control area). Such is the case after each moderate size BO, being required a considerable amount of "forensic" analysis over the information available to finally establish the causes and the full extent of the failure. In effect, such analysis can take months of work.

## **2.1 Generation and load Modifications**

Changing load conditions can be used as a corrective or preventive measure against most cases of overloading in grid lines. Once a threatening network state is detected, preventive action is exerted trying to drive the energy through the less loaded lines in the network. Such modifications can be achieved with a handful of actions, implying ascending degree of adjustment in the following order:

- i. A variation in the power injected by some of the

generators connected to the network.

- ii. Decrease the amount of power consumed by customers.
- iii. Modification in the structure of the network, by operating switches. This type of action can be used to add or remove line, generators, consumers, or to add energy transmission paths in the network.

This actions are carried out in some different ways, but in general terms have received the following names:

### **2.1.1 Power rescheduling**

In the electricity market, the power to be provided by each centralized generator is programmed in advance (which may be a couple of weeks, days, or hours depending on the power scale in play), usually under the supervision of a state agency to ensure transparency and market freedom with respects to the prices paid by energy. Modifying the pre-arranged power to be supplied by generators, is called rescheduling. The state of loading in the lines changes naturally, but the goal is to get an overall less stressed state.

This rescheduling, or redispatch, of the energy that each generator shall provide at a future time can be performed, for example, using the model of DC Power Flow, described in section 1.3.3, and is used in this thesis in chapter 4.

Since the energy demanded by users is constantly changing, (as well as the power delivered by some renewable sources like wind and solar), during normal operation of the network, i.e. without overload, the fine tuning of

the total power delivered by each generator is dynamically adjusted by automatic control systems, and commands from the control centers.

In large grids, which are divided into various control areas, each one run by an independent operator, rescheduling actions are also done by area operators, but only directly within their assigned area. Necessary adjustments on grid's nodes corresponding to neighboring areas (belonging to another operator), is done through coordination messages or requests to operators of the other areas. Such requests are meant to modify the amount of energy leaving or entering through the frontier lines that interconnect the involved areas.

Rescheduling is possible, even after a sudden change, only if the system is in a reasonable stable and static state. Although a basic control system can drive the system to reach a balance in which no line capacity is overwhelmed, rescheduling is inserted as part of a more elaborate control system to reach a more secure operation. The time between two credible failures and the need to make a re-dispatch is not normally a problem. That is, after the first credible failure there is little chance of another failure before reallocating power. On the other hand, it has been seen from past cascaded failures, that in a big number of cases, (73.5%, [20]), a first accidental failure was followed by a malfunctioning of a protection device, i.e. a hidden failure. That's why even using the n-1 security rule (see section 2.3), BOs can emerge in a "more than expected" rate [27]. More details regarding N-k security rules and contingency analysis is discussed in section 2.3. (Rescheduling of power is used in chapter 4 section 4.1.1) .

### 2.1.2 Load shedding

A clear definition of what load shedding is, was Given in [28] as follows: "This emergency measure involves the deliberate interruption of selected, least critical load in an attempt to avoid the interruption of all load on a system as a consequence of excessive decay in system frequency following a breakup of an interconnected transmission network. Load shedding may be done manually, under the monitoring of an operator, or automatically, initiated by under frequency relays. In either case, the amount and location of load to be interrupted to meet an emergency situation must be analyzed before the fact in order to judge its effectiveness and to assess its impact on transmission line loadings. The basic criterion should be the avoidance of further loss of generation or transmission. On some systems, voltage reduction without disconnection of load current may be a practical expedient for securing relief. Load shedding, properly applied, can be a prudent emergency measure in maintaining overall system reliability for those systems which are characterized by high concentrations of load and generation, e.g. compact metropolitan systems, and for systems relatively isolated or remote from other systems and having limited interconnection capability relative to their load. Load shedding on a region-wide basis should be applied only after intensive study by individual systems, recognizing in each instance the particular generation-transmission configuration and the degree of interconnection. If introduced without sufficient study and analysis, it can become a hazard rather than a remedy since excessive load shedding within a given area can result for some instances in an over speed

or overload of generators and loss of transmission circuits, thus further contributing to the system disturbance".

In particular, the reduction in voltage as load shedding method is rarely used in most developed countries because it involves a violation of quality standards. In countries with less rigorous standards it is a common and effective practice.

When load shedding is carried out following cyclic schedule is called a rolling blackout. An alternative for prevention BO closely related to this technique is "greenout", which consists in the voluntary disconnection of some users to reduce the overall demand.

In case of a BO in development, current methods for connection-disconnection of equipment, power shed, etc., rely on the capacities of local lines to support more or less load, and in the available information about the state grid. Meanwhile the BO is still happening, having an influence on the entire physical grid, beyond the usual limit of any area control. So, local forecast can do little about large scale BO, since this phenomenon implies long distance effects and state influence.

## **2.2 On-line and off-line BO foreseeing**

In BO prevention, collecting and classification of "problematic cases" is a way to be aware in advance of dangerous states. This collection of clues can be done by means of statistics on past events, or by simulation of possible future states taking as starting point the present grid conditions. The statistical approach is more suited

for traditionally trained human experts, while the "on-line prediction" via simulation, is the modern trend, (see next section). Depending on the size of the grid considered, the last approach, could need significant processing power, but it is the natural way to avoid accidental human errors, get standardization in grid behavior, and run assessment techniques in a systematic and documentable way.

### **2.3 Contingency Analysis (CA)**

Real time power grid operations heavily rely on computer simulation. A key function in the energy management system is contingency analysis, which assesses the ability of the power grid to sustain various combinations of power grid component failures based on state estimates. The outputs of contingency analysis, together with other energy management functions, provide the basis for operation, preventive and corrective actions. Contingency analysis is also extensively used in power market operation for feasibility test of market solutions, [29]. Contingency analysis uses the current state reported by SCADA systems to identify possible series of component failures and check for collapse cases. The CA schemes are usually referred to as  $(N - x)$  CA, where  $N$  is the total number of components (could be lines, generators and transformers) in the grid under consideration and  $x$  is the level or order of the analysis.  $N - x$  CA represents checking all possible permutations of  $x$  or less components (out of the total  $N$ ) for a collapse. For example, a  $N - 5$  CA would evaluate all possible combinations of up to five components failing together in a cascade. As the number

of components  $N$  and number of levels  $x$  increase, the number of possible combinations that need to be evaluated increases exponentially. Due to this computational complexity, contingency analysis has been traditionally limited to selected  $N - 1$  levels, exploring only the "most credible" possible failures. However, post event analysis of major blackouts has shown that failing of a component leads to additional component outages in its vicinity, [12]. If a grid passes a  $N - 1$  contingency analysis, it is said to be " $N - 1$  secure". The type of CA described here, have been developed for its use in power grids; furthermore, a simpler type of contingency analysis can be applied for complex networks of any type in order to grasp general robustness thereof. In section 4.3 one novel variation of such analysis is presented.

## 2.4 Successful methods?

While all methods to prevent or combat BO are forced to use some of the actions described in the previous section, the variety of proposed algorithms in use is quite big. How to implement the best network protection is the big unanswered question by now. There are many differences in the way in which the authorities in each country do introduce constraints to the operation of their networks; and probably the same control algorithm could eventually show mismatching results when tested on different networks. Reaching a conclusion of how good a control technique is from the point of view of BO prevention, is also hard because the sporadic nature of BOs. No matter the prevention method or control algorithm employed, it

is impossible to estimate whether the next BO will be greater or smaller than the last one. Anyway, because the problem itself is complex and difficult to attack in a deterministic way, the algorithms preventing faults are intensively incorporating computational intelligence techniques, to exploit different sources of information available at a time. Thus, the statistics from past failures, actual measurement data and predictions from simulations are used for determining whether the network is in a risky state or not. Some of the paradigms by which intense research is trying to implement state predictors and alerts are, for example, neural networks, genetic algorithms, particle swarm algorithms, intelligent agents and ant colony optimization, [30].

Anyway, the behavior of any controller using some of those techniques can be quite poor if they are not fed with features containing relevant information about the phenomenon of interest. Try to find indices, as discussed in this thesis to better understand the operation of the grid, and to be used as input features to those computational intelligence techniques, remains extremely valuable.

# 3 Security, robustness, reliability indices and parameters

WE can talk about indices of safety, robustness, or reliability when we have objective quantities by which it is possible to assess or predict in some extent the performance of the grid in relation to some phenomena (as BO or any other), or in relation to any type of test. Regarding this thesis, the focus is on BOs and indices that could be used automatically for control or planning algorithms to achieve better performances from the grid against those events.

In this chapter, I briefly review some of the indices so far more used to determine robustness and reliability of networks. I also mention some indices that have been defined to measure in some grade the extension or size of BO phenomena, but independently of any specific index regarding the state or components of a grid.

As first thought, it would be expected for an index to be a scalar quantity, but because of the number of variables involved and the complexity of power grids, the

potential of vector quantities as usefulness indices can not be discarded. In our case, confronting the BO problem, what we are interested to get are ways of showing:

- If the network is more or less at risk of a cascading failure .
- If is it possible to achieve grid operation with fewer BOs.
- If is it possible to get a reduction in the size of BOs.

One thing to note is that to define indices for more realistic situations, it is necessary to use more variables and data about the grid components involved. Naturally, the potential usefulness of an index is also increasingly limited to particular situations, and sometimes evaluating their performance has an increased difficulty.

Next, some of the indices that have been used in research and assessment on power networks are commented.

### **3.1 Structural or Topological Indices**

Purely structural indices, which take into account the network topology, are relatively simple when compared with those which try to consider the electrical quality of power grids. Structural indices are strongly based on the information that can be obtained from the corresponding network graph, [31]. The firsts of this group normally employed, have the particularity of being fairly generic, and as a rule of thumb were designed within the scope of study of complex networks. The idea of these indices is to capture universal features of systems as networks

made up of smaller components. They share their relative simplicity, and its usefulness as a tool for comparing systems of different nature.

### 3.1.1 Degree Index

This is the simplest of the topological indices in use. It is referenced to a node of the network, and consists in the quantity of other nodes connected to the reference one. Degree index is the number of neighbors a node has.

May be more important than the degree of each node is the probability distribution of all degrees in a network. Such distributions has been found useful for comparing various networks. It can even show similarities in networks of different nature and differences in networks of the same type. For example distributions of degree coefficient following a power law are normally found in some complex networks (as in metabolic networks, WWW, actor and scientific collaborations):

$$P(k) = a k^{\gamma_{pw}}.$$

Other common degree index distributions found in complex networks are, random and Poisson. Power law, exponential and intermediate distributions of these two are the most common found. For electric power grids the distribution is usually an exponential function [32] :

$P_{cum_{exp}}(k) = C e^{-k/\gamma_{exp}}$ . (With  $k$  being the degree coefficient;  $a$ ,  $C$  and both  $\gamma$ 's constants).

The average node degree is also a valuable index when comparing networks. In the case of power transmission grids, the mean value of degree coefficient is around 1.5.

### 3.1.2 Network Diameter

The diameter of a network (and its associated graph) is the maximal distance between any pair of its nodes [33]. In the case of power grids, distance between nodes have been considered as simply the minimum number of lines between two nodes. Also, more tuned to the electrical quality of power grids, the impedance of such chain of lines have been considered as a measure of distance. Other combinations of electrical properties of components have been used also to define distances and diameters.

### 3.1.3 Clustering Coefficient

Clustering coefficient is a measure of how much a group of node is forming a clique around an element. Nodes having high values for this coefficient tend to operate in "synchrony" as an unique element. The definition of this coefficient is [34]:

$C_i = \frac{2E_i}{k_i(k_i-1)}$ . Where  $C_i$  is the clustering coefficient of node  $i$ ,  $k_i$  its degree coefficient, and  $E_i$  is the number of edges or connections among the existent  $k$  nodes surrounding  $i$ . This coefficient in combination with diameter, is capable of bringing in light some properties of networks as for example the grade of similarity with "small world networks" or with "random networks" as described in [34]. Other simple combinations of topological coefficients could also be interesting and beneficial to extract or represent important features of networks, and used as a kind of vector indices. In this thesis, combinations of two indices are explored in chapter 4, one of such pairs including the clustering coefficient.

### 3.1.4 Centrality and Betweenness Centrality Coefficients

Centrality coefficients try to capture the importance or relevance of an element in a network in relation to the others, without regarding whether they are near or far. These coefficients have been defined as a way to capture how influential and connected to the remaining of the network a reference element can be. Also how much the connection between other elements is dependent on the reference element.

The idea was originally developed to indicate, in social networks, which are the most influential people. Someone who is known by many other people, for example, can help a new network integrant to connect easily with other people. That is to say, the new member can form more bonds with others if he first connects with someone who is already strongly connected to the rest of the network.

The simplest measure of centrality in the sense of connection strength to the network that can be adopted is the degree coefficient, but this is a highly local measure, taking into consideration only the very near elements to the reference one. As centrality is a concept trying to capture also distant influences, the distance to far elements of the network are normally taken into consideration for definition of centrality indices. To act as a relevant link between two others, the reference element is supposed to be in a point inside the minimum length path between the other two.

One of the most interesting centrality coefficient devised is the Betweenness Centrality (BC). This is defined as the ratio of the number of minimal paths passing

through the reference element and connecting any pair of other elements, over the total number of minimal paths connecting the pairs of elements [35], [36]. BC can be defined for any type of element in a graph, i.e. nodes or edges, being the definition for nodes as follows:

$$BC(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} \quad (3.1)$$

That is, the "betweenness centrality of node  $v$ ", (where  $\sigma_{st}(v)$  is the number of minimal length paths between two generic nodes  $s$  and  $t$ , and going through the node  $v$ ; and  $\sigma_{st}$  is total number of minimal paths connecting nodes  $s$  and  $t$ ).

This definition only takes into account the structure of the graph corresponding to a network; however this measure of centrality has been found to be very representative of the importance of nodes in some real networks, as network data transmission systems. Anyway, for other types of networks it is not so useful. To be used in power grid research many other centrality indices have been defined by different research groups.

Some of those centrality coefficients are for example: Eigenvector Centrality, Closeness Centrality, Electrical Degree Centrality defined as in [37], centrality delta [38], and many more.

In this thesis, a coefficient of electrical betweenness, is presented in Chapter 4 whose definition takes into consideration several characteristics of the electrical network.

## 3.2 Indices for BO assessment

Besides those already mentioned, there is a huge amount of research that have linked topological and electrical betweenness indices to BOs. As a general rule, what is sought are quantities showing influence on the behavior of grids against cascading failures. In general such studies serve to get an idea of the weakest and the strongest points on a network, obtained by extrapolating the relationship between BO and such indices. Also, threatening loading states has been related to betweenness. Any index capable of highlight strengths or weaknesses in the network is worth to be considered for further development. The most used way of working in this field (BO on power grids) is to define an index and then cause cascading failures in modeled power grid; subsequently measurement of the size or amount of failure are collected, and relations with the defined index under test are established if possible.

This performance evaluation of network and at the same time of the proposed indices also requires many times the use of a more or less original way to measure and expressing the results. This fact can be seen as a way of defining indices, which are able of putting in evidence information contained in the results of simulations. In this sense, for example, probability distributions made with data from BO (simulated or not) can be considered as useful standard indices.

The following section will briefly discuss some of these indices intended as gauges to measure the response of a network against BO. In chapter 4 some alternative ways to show the performance of a grid in reference to BO are shown.

### **3.2.1 Some assessment indices**

Many indexes to measure the reliability of a grid against service failures and BO have been proposed, some of the simplest are for take into account the result of:

- Measurements of the frequency or duration of short service interruptions.
- Measurements of the frequency or duration of long service interruptions.
- Measurements of frequency and depth of voltage drops

As examples of these types of indexes are some of the mentioned in the recommendation IEEE 1366 [39], which is a guide that can be useful in some cases, and can vary in its use when working with different grids.

Indices for sustained interruptions:

- SAIFI: system average interruption frequency index.
- SADI: average duration index system .
- CAIDI: Customer average interruption duration index.

These indices are meant to show how robust was the network behavior, in normal operation or after a test. In case a new technique or control algorithm should be tested, it is assumed that these indices can be used to make a comparison with performance obtained from previous algorithms.

## 4 ORIGINAL INDICES

**T**his chapter consists of 3 main parts focusing on different approaches searching new clues about how to improve the performance of power grids against BOs, namely: "Economical Dispatch and BOs", "Distributed Generation and BOs" and "Combined Indices for Static Contingency Analysis".

Justifications and results of three corresponding groups of experiments carried out on transmission network models are displayed.

Summarily, any original idea of this thesis is contained and developed in this chapter.

### **4.1 Economical Dispatch and BOs**

In the market of electric energy, the operation of power grids in the most economical way is a major objective, i.e. producing and transporting energy at the minimum possible cost [40]. At the same time security and environmental

regulations must be fulfilled, and compromises between economic operation and technical limits of grids must be addressed.

Seeking for the most economical generation and transport solution (Economical Power Flow - EPF), normally leads to the commitment of generators with lower operation cost to provide most of the consumer required power, while the remaining power is provided by the less efficient generators [41]. This is actually just one of the possible solutions to the generic dispatch problem (DP), that strives to satisfy all the load with the available generators by simultaneously fulfilling some target of interest.

Some restriction to the goal of maximum profit is always present, since each constituent of the network has safety working conditions beyond which it should not be used [42]. When sudden fluctuation of load happens, deviation from optimal dispatch can be exercised to avoid overloading of grid elements; but after a while the most economical working point under the new conditions is wanted again. Economy and security seem to be antagonistic with each other. However, from the perspective of BO propagation this trend claims to be verified since, sometimes, efforts made to reduce the risk of smaller blackouts can increase the risk of large blackouts [18].

When using an EPF, nearly overloaded lines may exist in the system even if the total power generated is relatively low compared to the total transmission capacity of the network. Therefore, even at low load levels, stressed network elements may fail and trigger a BO of a not necessarily little size. To reduce such kind of threatening states, some variations in dispatching may be adopted:

- i. Deploy Distributed Generation (DG), i.e., providing power sources closer to load nodes. This approach basically tends to reduce criticalities due to transmission grid. (If all loads were supplied by a local generator, the grid lines wouldn't be needed). Advantages of DG in reducing BO has been explored numerically in [8] by means of models similar to the presented here.
- ii. Try some uneconomical power dispatch (non-EPF) having line integrity as major objective, i.e. a rescheduling of power generated at each of the centralized generators, typically at a higher cost with respect to the minimum possible. Non-EPF dispatch is expected to be an intermediate solution between DG and EPF, from either economic and robustness against BO performance standpoints. Although such behavior sounds easy to accept, a verification of this statement have not been made before. Also, the numerical quantification done here is worth, since BO processes could produce unexpected results [18].

A comparison, between EPF and non-EPF is made in the following sections in order to verify numerically the mentioned supposition, and to evaluate the most appropriate dispatch policy according to the loading state of a grid. We explore how blackout sizes change when power dispatching is done using different policies. The uncoupled DC models of IEEE power grids test cases 30, 57 and 118 are used to run the experiments, [43]. This networks are portions of the USA power grid and among others have been used as reference structures for many

years. The denomination "118" and "162" indicate the number of buses, or nodes, of each of these networks.

To pre-assign the quantity of power produced by each generator, a general nonlinear programming method as explained in [44] is useful, since operational cost of generators are normally nonlinear functions. However, the supposition of low complexity for generator cost functions is made here, considering the situations in which linear approximations are acceptable [45]. Further to that, the simple "DC power flow method" ([46], and section 1.3.3) is employed, which is fully linear, and produces good estimation of the active power flows going from generators to loads. Due to this ability [47], DC model has been used formerly in BO simulations as in [18], [48], [49], [50]. Hence, by taking these two assumptions regarding the employed models, most of the power dispatching task can be modeled as a linear programming problem.

In section 1.3.3 the linear relation used for modeling the electric characteristics of grid and power flow, was indicated in equation 1.7

$$F = MP$$

Among the entries of the vector  $P$  may be some 0's (corresponding to transmission nodes), some are fixed (those corresponding to loads) and some are the actual unknowns of our dispatch problem (the values of power corresponding to generators). Based on this distinction it is convenient to rewrite the linear relationship between net powers and flows as

$$F = AL + BG \tag{4.1}$$

where the matrices  $A$  and  $B$  contain proper combination of topological structure and reactances of the grid, and

give the effect on the flows produced by loads  $L$  and by generated powers  $G$ .

### 4.1.1 Dispatching and re-dispatching power

With the above notation, the solution of a DP amounts to the solution of a linear or nonlinear programming problem with a certain objective function and some constraints that, starting from equation (4.1), define the network topology and limitations.

Now, each generator is associated to a generation cost  $c_i G_i$ , ( $i = 1, \dots, I$ ) by means of the unitary generation cost  $c_i$  so that  $\sum_{i=1}^I c_i G_i$  is the total generation cost minimized by straightforward EPF solutions.

A pre-requisite to comparison of different dispatch policies is the computation of the maximum energy that can flow through the network. This will allow us to qualify the stress to which the grid is subject in operating conditions as the ratio between the total power actually dispatched and such a maximum.

### 4.1.2 Transmission Capacity Estimation

The maximum grid transmission capacity is estimated by solving

$$\begin{aligned}
 \max \quad & \sum_{j=1}^J L_j \\
 & \sum_{i=1}^I G_i = \sum_{j=1}^J L_j \\
 & F = AL + BG \\
 \text{subject to} \quad & |F| \leq C \\
 & G \geq 0 \\
 & L \geq 0
 \end{aligned}$$

where vector inequalities have to be read component-wise, and the loads are taken as unknowns.

Since there is no bound on the amount of power injected into the grid by the generators, the solution of the above problem depends only on the capacities of the lines listed in the vector  $C$  and tends to saturate all the possible paths from generating nodes to load nodes.

The maximum of the objective function,  $Q$ , is assumed to be the maximum total transfer capacity of the network and is used to parameterize the level of *stress* to which it is subject.

### 4.1.3 Building the reference case

Such a parameterization is done by considering load configurations such that  $\sum_{j=1}^J L_j = \gamma Q$  with  $\gamma \in [0, 1]$ . To simultaneously build the load configuration and associate to it the most economical dispatch power, the following linear programming problem is solved:

$$\begin{aligned}
 \min \quad & \sum_{i=1}^I c_i G_i \\
 & \sum_{i=1}^I G_i = \sum_{j=1}^J L_j \\
 & \sum_{j=1}^J L_j = \gamma Q \\
 \text{subject to} \quad & F = AL + BG \\
 & |F| \leq C \\
 & G \geq 0 \\
 & L \geq 0
 \end{aligned}$$

where both the vector  $G$  and the vector  $L$  are degrees of freedom that are fixed by the optimizer in a feasible configuration conforming to the chosen stress parameter  $\gamma$ .

Since we are interested in values of  $\gamma$  that are close to 1, feasible load configuration typically entail many non-null entries and well represent highly-loaded grids.

#### 4.1.4 Uneconomical Dispatching

With the same loads determined in the previous section (and thus for the same stress level) a different approach to dispatching is used, which solves the following programming problem:

$$\begin{aligned}
 \min \quad & \sum_{k=1}^K \left| \frac{F_k}{C_k} \right| \\
 & \sum_{i=1}^I G_i = \sum_{j=1}^J L_j \\
 \text{subject to} \quad & F = AL + BG \\
 & |F| \leq C \\
 & G \geq 0
 \end{aligned}$$

Note that, in this case, the entries of the  $L$  vector are not degrees of freedom and that generation cost is not taken into account. Rather, the aim is making lines as far as possible from their maximum capacity thus favoring the use of alternative paths between the same pairs of nodes and implicitly enhancing robustness with respect to possible localized failures.

Despite the presence of an absolute value, the above problem can be recast into a linear programming problem by the classical method (see, e.g., [51]) of adding a further variable vector  $X$  with the same size of  $F$ , adding the constraints  $F \leq X$ ,  $-F \leq X$ ,  $X \geq 0$ , and minimizing  $\sum_{k=1}^K X_k$ .

The corresponding solution will be indicated as uneconomical Linearly Penalized Power Flow (LPPF). A similar

dispatch method can be sought by minimizing the summation of line flow, in absolute values, that is using  $|F_k|$  in place of  $|F_k/C_k|$  to minimize

$\sum_{k=1}^K |F_k|$  in the preceding programming problem.

Another dispatch policy, intended to emphasize further that small flow values have to be preferred against larger ones, can be thought using a second-order nonlinearity and making the dispatch problem equivalent to the quadratic programming problem

$$\begin{aligned} \min \quad & \sum_{k=1}^K \left( \frac{F_k}{C_k} \right)^2 \\ & \sum_{i=1}^I G_i = \sum_{j=1}^J L_j \\ & F = AL + BG \\ \text{s.t.} \quad & |F| \leq C \\ & G \geq 0 \end{aligned}$$

The corresponding solution will be indicated as Quadratically Penalized Power Flow (QPPF).

#### 4.1.5 Blackout simulation and measurement

To initiate a BO we trip a randomly selected grid line.

After each failure (let it be the initial or any subsequent one) the matrices  $A$  and  $B$ , and  $F = AL + BG$  are recomputed. If the new set of flows entails lines that overcome their capacities, the highest flow line is tripped and flows, recomputed.

If this cascaded tripping isolates the  $\bar{i}$ -th node with either  $L_{\bar{i}} > 0$  (a load) or with  $G_{\bar{i}} > 0$  (a generator), power unbalance takes place and we have to tackle it by

means of either load shedding or generation re-dispatch respectively.

- If  $L_i > 0$  then the total load decreases and the dispatch problem is solved again with the previously adopted strategy (EPF, LPPF, ...) and adding the constraint  $|G - G'| \leq \epsilon$  where  $G'$  are values of the powers injected into the grid previous to re-dispatch;  $\epsilon > 0$  is a threshold accounting for the limited ability of generators in following rapid transients.
- If  $G_i > 0$  then less power is available over the grid and we must proceed with load shedding.

To minimize transients, the generators still injecting power into the grid do not change their production while we try to reduce the shedding of load. This is achieved by solving the linear programming problem

$$\begin{aligned}
 & \max \quad \sum_{j=1}^J L_j \\
 & \quad \hat{\eta} \sum_{\substack{i=1 \\ i \neq \bar{i}}}^I G'_i = \sum_{j=1}^J L_j \\
 & \quad F = AL + BG \\
 & \text{s.t.} \quad |F| \leq C \\
 & \quad 0 \leq L \leq L' \\
 & \quad 0 \leq \hat{\eta} \leq 1
 \end{aligned}$$

where  $G'$  is the vector of pre-shedding generated powers,  $L'$  is the vector listing the pre-shedding load levels, and  $\hat{\eta}$  is an additional variable whose final value indicates whether the remaining power can be distributed without causing the failure of a further link. In fact, if the solution sets  $\hat{\eta} < 1$ , the power of

the generators cannot be entirely distributed to the loads without violating some capacity constraint. To cope with this, the most loaded line is assumed to have a failure and the load-shedding is repeated with the new grid topology.

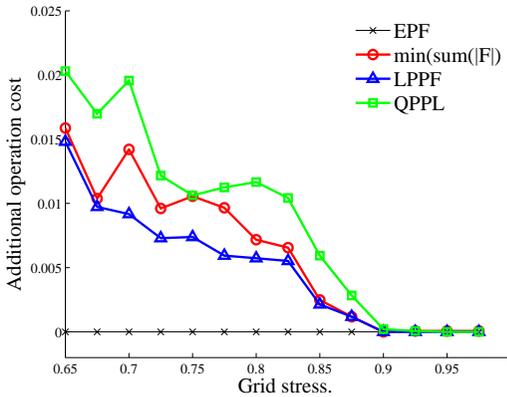
#### 4.1.6 Results

For each considered value of  $\gamma$  a BO is initiated in each line of the grid. Moreover, to prevent results from being dependent on the unit generation costs, for each BO starting point and  $\gamma$ , many simulations are carried out with different randomly drawn values for the  $c_j \in (1,2)$ , to estimate average behaviors. The BO is allowed to progress even if the grid becomes divided into sections. Additionally, as we induce BOs and let them to propagate, the generated powers and flows on lines must be recalculated inside the corresponding grid section, each time an element is overloaded and disconnected. The simulations show that, when some of the non-EPF dispatch is used, the average total power loss due to a BO can be less than when using only EPF. The figures show results of simulations for "IEEE 57 Bus, Power System Test Case" [43], using the proposed non-EPF methods on values of  $\gamma$  from 0.65 to 0.975, (high BO threat), and 2500 different sets of random costs for each  $\gamma$ .

On figure 4.1 the average extra costs of operation of each dispatching method are displayed, taking the cost of operation at grid capacity as scale reference. This is the increase in operation cost due to the adoption of a non-EPF in routine conditions. Regrettably, total costs associated to BO depend also on the effectiveness of re-

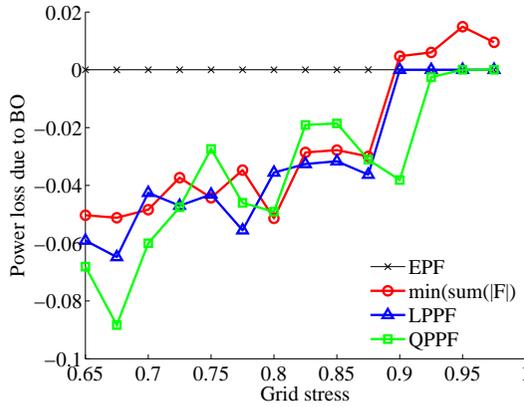
covery plan; which is a time dependent (after BO) variable out of the modeling scope adopted. We concentrate here in costs of generation previous to BO's occurrence. Values corresponding to EPF are taken as zero reference. This is the cost we must incur to achieve more robustness, since it is expected for some non-EPF methods a reduction of BO-related losses.

Figure 4.2 shows the average power loss produced by each dispatch method at the end of BO propagation. Grid capacity has been taken as scale to measure the power loss of each BO: the average values are calculated on the results from all the lines and sets of random  $c_j$  for each  $\gamma$ . The averages obtained for EPF were taken as zero reference, therefore the corresponding losses (of EPF) lay on the horizontal axis of figure 4.2.



**Figure 4.1:** Average additional costs for non-EPF. The costs of generation when using EPF are taken as the reference.

It is evident from figure 4.1 that non-EPFs are more expensive than EPF, but method LPPF is cheaper than QPPL. On the other hand, methods LPPF and QPPL show



**Figure 4.2:** Average power loss due to a BO. Losses for BOs when using EPF are taken as reference.

negative values of excess power loss, which is the major result of the experiments.(i.e. Power losses for this two dispatch methods are less than those for EPF, which have been taken as reference). Conversely, the remainder method,  $\min(\sum(|F|))$ , can produce power losses in excess as well as excessive operation costs. Therefore, this method is not recommended for utilization.

Comparison between LPPF and QPPF methods is not clear from figure 4.2, although QPPF seems to have more sensible effects for greater values of  $\gamma$ . To decide this question, a simple summation (integration) of each set of values can serve, under the simple assumption that all  $\gamma$  are equally probable over time. Summations of excess BO power loss results equal to -0.45 for method LPPF and -0.5 for method QPPF; whereas, summations of operation excess costs is 0.07 for method LPPF and 0.12 for method QPPL. Achieved reductions in BOs losses are almost the same, while excess cost of QPPF method is clearly bigger

than for LPPF.

#### **4.1.7 Stress and Dispatch policies as new indices**

In this section, objective evidence was presented to support a previously unproven statements: "Doing the grid safer is also more expensive". The results show that, effectively, some non-EPF dispatch policies can reduce mean BO sizes in comparison to EPF technique. Simulations on others test systems (IEEE 30 bus, IEEE 118 bus) produce similar results, showing as preferable the use of LPPF method for moderate  $\gamma$  and QPPF only for higher values. It is true but the important point here is having done comparisons directly against an algorithm of dispatch which strives for reaching the point of minimum cost. The number of constraint inside control algorithms, joined to the complexity of the grid, don't allow to take any statement as true without some experimentation.

(More on this topic is addressed in chapter 5.1).



## 4.2 Distributed Generation and BOs

In this section it is shown how outage shift factors (OSF) can be used to define a synthetic indicator of node importance in power grids. A simple OSF-based index is used jointly with Electrical Betweenness to select power sources locations in a distributed generation framework. Simulation indicates that blackout rejection is non negligibly enhanced by this combined approach.

### 4.2.1 Where to place DG?

Large generation units normally have a fixed site on a power grid since early design stages; this is not the case for medium and small sized generation equipment, which mostly constitute DG (distributed generation). Where to place this medium sized type of power generation in a mature grid is not a trivial task, and is a topic of major interest in modern electric markets [52]. Research has mainly concentrated on reduction of power loss, production costs, and enhancement of voltage stability in distribution networks among others objectives; and less interest have been seen on the effects of DG over cascade failures and BO. Intuitively DG must have a beneficial effect on transmission infrastructures [8] but, more detailed analysis suggest that robustness of transmission grids can be degraded, increasing the risk of large failures, with increased distributed generation if not done carefully [53]. As DG is progressively taking a greater portion of the total generation, its impact on BO is not to be neglected.

### **4.2.2 Betweenness and shift factor combination**

As mentioned in chapter 2, in order to protect grid's component from cascade failures a rather big number of ideas, techniques and theoretical models has been developed and are still under investigation, not only in the area of power grids but also in complex systems and communication networks. Among them, for example, betweenness coefficients have been defined to rank the vulnerability of network components, and betweenness-like coefficients have been produced also for power grids [36], [54], [35]. In [36] an Electric Betweenness (EB) was defined for ranking lines and nodes from the standpoint of security. Such EB definition, taken up in equation (4.2) and (4.3), is built from a linearized DC model of the grid (described in section 1.3.3), and is based on two properties of transmission lines: maximum allowed power flows and shift factors (SF).

EB are strongly dependent on the unabridged grid's structure (that is, the network characteristics before any failure), and therefore post-contingency grid's features are ignored. On the other hand, outage shift factors (OSFs) contain information about the after-contingency grid's structure, and so, the idea of using them to define security indices conceptually independent from EB is very appealing.

### **4.2.3 Method for DG site evaluation**

DG site evaluation is addressed here by means of a simple characterization of grid's buses as points for generation

placement, using a suitable combination of both EB and OSF grid topological indices, and evaluating the performance of the chosen buses via BO simulations. The methodology used consists in taking the set of generation buses as a degree of freedom, and changing its elements depending on some simple combinations of the topological indices. For each instance in those groups of buses a loading state is established and cascade failures are triggered. In real transmission grids large generation centers (as nuclear, hydro, etc.) have fixed locations on the network.

However, for the sake of letting the topological indices to show freely their effects, fixed generators or loads sites are not included in the numerical experiments, permitting all buses the possibility to host generation or load as different instances are tested.

#### 4.2.4 Grid Electric Model

Here, the same models as in section 4.1 are used.

The electrical characteristics of the grid are taken into consideration using the linear model for network, and the DC power flow calculation method as described in section 1.3.3.

Those can be summarized by equation 1.7 ( $F = MP$ ) and equation 4.1 ( $F = AL + BG$ )

(Where  $M = \{H\}$  is the matrix of shift factors).

The matrices  $A$  and  $B$  contain proper combination of columns of matrix  $H$ , and give the effect on the line flows produced by loads  $L$  and generated powers  $G$  separately.

### 4.2.5 Power delivering

For the experiments carried out in this section, basically the same methodology as in section 4.1.1 was employed with some modifications.

#### Network's Total Transmission Capacity

As in section 4.1.2, a pre-requisite to obtain comparable loading states for each set of generation-consumer nodes, transmission capacity, ( $Q$ ) requires to be calculated. Also to qualify the stress level ( $\gamma$ ) to which the grid is subject in operating conditions is used. Different combinations of supplied powers and loads should be comparable if producing the same level of stress to the network. The optimization problem to find the transmission capacity has the same form as in section 4.1.2, plus the addition of constraints corresponding to the "N-1" rule. Also the algorithm was adapted to change easily the nodes being generation, load or transmission.

$$\begin{aligned}
 & \text{maximize } \sum_{j=1}^J L_j \\
 & \sum_{i=1}^I G_i = \sum_{j=1}^J L_j \\
 & F = AL + BG \\
 & \text{subject to } |F| \leq C \\
 & G \geq 0 \\
 & L \geq 0 \\
 & \text{"N - 1" rule constraints}
 \end{aligned}$$

Regarding the  $N - 1$  security rule, we make the following assumption: if any single line fails, the generation and load levels (not modified) would impose a new flow regime ( $F'$ ) to the remaining lines. Being  $H'$ ,  $A'$  and

$B'$  the corresponding new matrices of shift factors, the optimization problem must guarantee that the lines flows do not overcome line capacities, that is:  $F' = A'L + B'G$ , with  $|F'| \leq C$ . Following this idea,  $N - 1$  rule constraints are formed using the three groups of matrices  $F'$ ,  $A'$ , and  $B'$ ; each group formed by  $K$  matrices, each of this corresponding to a grid without one of the  $K$  possible lines.

### Flow Calculation, General Case

Each generator is associated to a generation cost  $c_i G_i$  ( $i = 1, \dots, N$ ) by means of the unitary generation cost  $c_i$  so that  $\sum_{i=1}^N c_i G_i$  is the total generation cost. To simultaneously build the load configuration and associate to it the most economically dispatched power, we solve the following linear programming problem:

$$\text{minimize } \sum_{i=1}^I c_i G_i$$

$$\sum_{i=1}^N G_i = \sum_{j=1}^J L_j$$

$$\sum_{j=1}^J L_j = \gamma Q$$

$$F = AL + BG$$

$$\text{subject to } |F| \leq C$$

$$G \geq 0$$

$$L \geq 0$$

$$N - 1 \text{ rule constraints}$$

where both, the vector  $G$  and the vector  $L$  are degrees of freedom that are fixed by the optimizer in a feasible configuration according to the chosen  $\gamma$ . Since we are interested in values of  $\gamma$  that are close to 1, feasible load configurations typically entail many non-null entries and well represent highly-loaded grids.

### 4.2.6 Topological indices

#### Electric Betweenness

The Electric Betweenness coefficient (EB) used here, was inspired in betweenness centrality and the aim to consider more realistically the way power flows in an electric grid. It is defined in [36], as follows:

$$EB(v) = \frac{1}{2} \sum_{g \in \mathcal{G}} \sum_{l \in \mathcal{L}} T \sum_{k \in \mathcal{L}^v} |H_k^{gl}| \quad (4.2)$$

$$TC_g^l = \min_{k \in K} (C_k / |H_k^{gl}|) \quad (4.3)$$

where  $v$  is a generic bus, situated between a generation bus  $g$  and a load node  $l$ ;  $\mathcal{G}$  is the set of all generation bus in the grid and  $\mathcal{L}$  the set of load buses. The quantity  $T$  is the maximum power the grid would transport between bus  $g$  and  $d$  without producing a line outage in the hypothetical setup of  $g$  and  $d$  being the only buses with effective input and output power flow.  $H_k^{gl}$  is the shift factor (or power transfer distribution factor) on line  $k$  with respect to bus  $g$ , and taking bus  $l$  as reference. This can be obtained by simple subtraction of elements  $g$  and  $l$  of row  $k$  of matrix  $H$ .  $\mathcal{L}^v$  is the set of lines adjacent to bus  $v$ , and is used also in the definition of the next topological index.

#### Outage Shift Factor Index

When a transmission line  $m$  goes out of service in a operating grid, the  $k$ -th line that is still working suffers a change  $\Delta F_k$  in its power flow. Each of those flow changes is almost proportional to the pre-contingency flow of the lost line. The proportionality factors are the so called Line Outage Shift Factors, LOSF.

$$LOSF_k^m = \Delta F_k / F_k \quad (4.4)$$

A way for calculating these LOSF as function of pre-contingency power transfer distributions factors can be seen in [55]. So, the  $k$ -th non-failing line has an outage shift factor referenced to the fallen line  $m$ ,  $LOSF_k^m$ , that can be known just from the values of matrix  $H$  of the unabridged network. Alternatively, we can say that each line  $m$  has  $K-1$  associated LOSFs indicating how big is its influence over the other lines. To express such influence the OSF\_line index of a line  $m$  has been defined:

$$OSF\_line_m = \sum_{k=1}^{K-1} LOSF_k^m \quad (4.5)$$

and finally for each bus  $v$  in the grid, an OSF index has been defined (simply denoted by  $OSF(v)$ ) as the sum of the OSF\_line indexes of all its adjacent lines:

$$OSF(v) = \sum_{m \in \mathcal{L}^v} OSF\_line_m \quad (4.6)$$

Other bus outage shift factors exist in the Literature. For example the one shown in [46], was designed to consider the loss of a generator, and its value is dependent on an arbitrary selection of which of the remaining generator would supply the lost power. On the other hand, the OSF index in equation 4.6 is exclusively dependent on network topology.

### **Blackout simulation and measurement**

Before BO simulation, a state of load must be set on the network, choosing generation, load and transmission nodes, and a stress level. Cost associated with generation

and loads are also renewed for each load state, as a way of take into consideration variable consumer requirements.

To initiate a BO event, a first line is cut and taken as a reference. After this trip, the network is still stable since its load state was established fulfilling the  $N-1$  rule. So, a second line must be forced to outage if it is desired to trigger any spreading perturbation. Since the stronger influence of a failed element is normally on the nearest components of the grid [20], we take the second failed lines from those which are adjacent to the first failed one.

After each failure (let it be the two initial, or any subsequent one) we re-compute the matrices  $A$  and  $B$  and  $F = AL + BG$ . If the new set of flows entails lines that overcome their capacity, the highest flow line is tripped, and flows recomputed.

If this cascaded tripping isolates the  $i$ -th node with either  $L_i > 0$  (a load) or with  $G_i > 0$  (a generator), power unbalance takes place and we have to tackle it by means of either load shedding or generation re-dispatch respectively.

- If  $L_i > 0$  then the total load decreases and the dispatch problem is solved again adding the constraint  $|G - G'| \leq \epsilon$  where  $G'$  are values of the powers injected into the grid previous to re-dispatch;  $\epsilon > 0$  is a threshold accounting for the limited ability of generators in following rapid transients.
- If  $G_i > 0$  then less power is available over the grid and we must proceed with load shedding.

To minimize transients, the generators still injecting power into the grid do not change their production

while we try to reduce the shedding of load. This is achieved by solving the linear programming problem:

$$\begin{aligned}
 \max \quad & \sum_{j=1}^J L_j \\
 & \hat{\eta} \sum_{\substack{i=1 \\ i \neq \bar{i}}}^I G'_i = \sum_{j=1}^J L_j \\
 & F = AL + BG \\
 \text{subject to} \quad & |F| \leq C \\
 & 0 \leq L \leq L' \\
 & 0 \leq \hat{\eta} \leq 1
 \end{aligned}$$

where  $G'$  is the vector of pre-shedding generated powers,  $L'$  is the vector listing the pre-shedding load levels, and  $\hat{\eta}$  is an additional variable whose final value indicates whether the remaining power can be distributed without causing the failure of another link. In fact, if the solution sets  $\hat{\eta} < 1$ , the power of the generators cannot be entirely distributed to the loads without violating some capacity constraints. To cope with this, the most loaded line is assumed to have a failure and the load-shedding is repeated with the new grid topology.

#### 4.2.7 Blackout measurement, and probability-risk graph.

BO size is measured as the loss of supplied power once the cascade of failures reaches to a stable point. Additionally, to compare BO from different load instances, BO sizes are weighted by the transmission capacity of the grid loading instance.

The set of all relative sizes from different BO have a cumulative distribution probability (CDF) function, accounting for the probability of a BO being less or equal than a chosen value. Starting from this, the complementary CDF, (CCDF=1-CDF) can be effectively employed to assess the ability of grid rejecting significant-size BOs. In fact, given a threshold value for the BO size it is the probability that an event producing a loss exceeding that threshold exists and, ultimately, how risky is a certain grid configuration. Obviously, when plotting CCDFs against the threshold, the lower the profile, the greater the robustness of the grid.

## Results

The basic idea of the experiments consist in changing the position of generators and make an evaluation of the vulnerability of the resulting grid. The selection of position to insert generating and consuming buses onto the grid is made based on the values of *EB* and *OSF* indices. No fixed generator or load is taken into account. To calculate electric betweenness of each bus  $v$  using equations (4.2) and (4.3) all the others nodes are considered as possible input and output points. That is, any of the others buses can be in both sets,  $Ld$  and  $Gn$ .

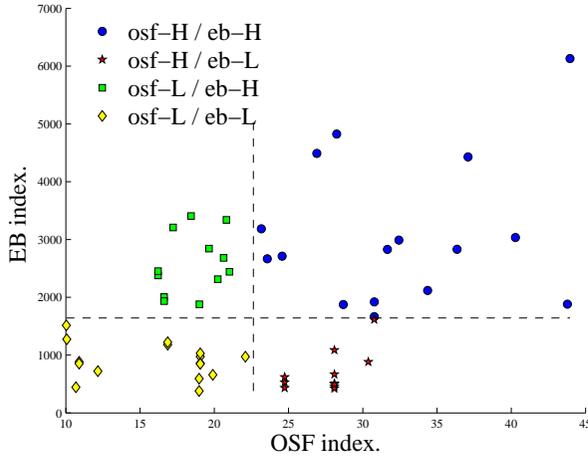
The values of the two indices for the "IEEE 57 Bus, Power System Test Case" [43], can be seen on figure 4.3. Also there are on the plot the median of *OFS* values (vertical line) and of *EB* values (horizontal) line. Median thresholds are used to conventionally separate low values from high values of parameters. Note how points are scattered in the EB-OSF plane with a correlation equal

to .38, that allows to use the two indices approximately independently.

After obtaining the two topological indices for all the buses of the tested grids, three type of runs have been carried out depending on the selection of nodes in which generation units are allocated:

- i. Input nodes selected using the values of just one of the topologic indices, depending whether the index value is above or below the median. In this way, four different sets of instances have been generated, two for generators placed on nodes with a high value index, namely: `osf_H` and `eb_H`; plus other two, for nodes with lower values of the index: `osf_L` and `eb_L`.
- ii. Input nodes selected using the four possible combination of high or low values of the two indices, namely: `osf_H/eb_H`, `osf_H/eb_L`, `osf_L/eb_H` and `osf_L/eb_L`.
- iii. Input placed randomly regardless the value of any index, used as a control set to show network behavior independent from the indices.

For each instance of generation and consuming nodes a number of variable load conditions are considered by taking random values for the generation cost,  $c_j \in (1, 2)$ . After the loading conditions are established, a BO is initiated in each line of the grid, and is allowed to progress even if the grid becomes separated into sections. As the intention is to show the performance of indices in high stress situation, a fixed value of  $\gamma = .995$  (high BO threat) has been taken for all the instances. Additionally, BOs are induced and let to propagate, and the generated



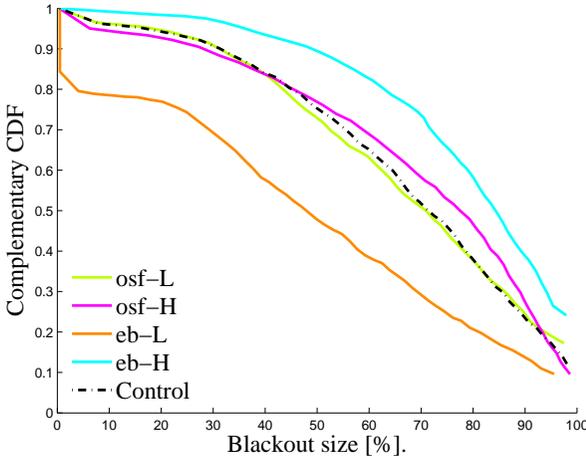
**Figure 4.3:** Electric Betweenness vs. OSF index.

powers and flows on lines must be recalculated inside the corresponding grid section, each time an element is overloaded and disconnected.

The figures show results of simulations for "IEEE 57 system", and 1000 different instances of nodes and loading states, imposing 5 generation and 20 consuming nodes for each instance.

Figure 4.4 shows results for the first type of runs. Reading an abscissa (BO size %) on this graph, the corresponding ordinate indicates the probability of occurrence of BOs of size equal or greater than the abscissa. A higher line indicates greater chances for big BOs. Clearly the best positioned set of runs is L<sub>eb</sub>, corresponding to generators located on buses of low EB. Also, the effect of EB is more intense than OSF since the runs corresponding to this last are closer to the control set.

However these conclusions must be completed with



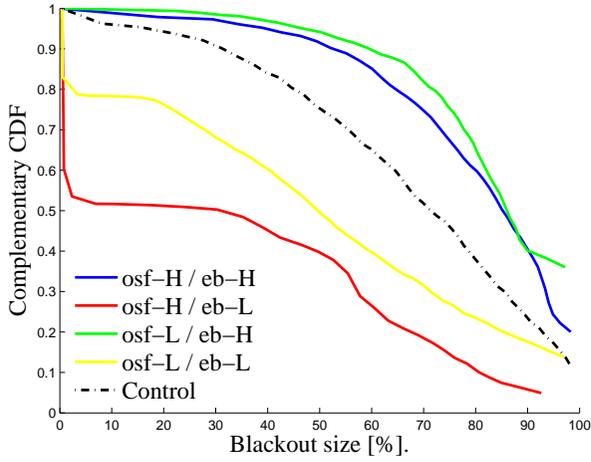
**Figure 4.4:** Risk-impact / Probability for the first sets of buses.

figure 4.5, which shows results from of the second type of runs. Here, the seemingly scarce influence of OSF index vanishes, showing a systematic effect when combined with EB. What can be observed is a net reduction of big BO when generators are confined to one of the two set of nodes with higher OSF index.

The best set of nodes to insert generators is the one with high outage shift factors and low electric betweenness (osf\_H/eb\_L).

#### 4.2.8 OSF index usefulness

This new topological index (OSF), based on post-contingency grid structure has the potential to enhance the selection of generation placement from a BO size reduction point of view. It works effectively in conjunction with electrical betweenness in identifying nodes that are best suited to



**Figure 4.5:** Risk-impact / Probability for the second sets of buses.

host generation devices.

(More on this topic is addressed in chapter 5.2).

## **4.3 Combined Indices for Static Contingency Analysis**

### **4.3.1 Static Contingency Analysis (SCA)**

Dynamical Robustness Analysis, and contingency analysis (section 2.3) on power grids entails the consideration of power flows, and constraints like capacities of lines, generators and others grid's components. This allows the observation of some realistic effects, as for example: when a grid element failures its zone of influence can arrive to distant location, not being limited to nearby components.

On the other hand, Static Robustness Analysis is simpler, just because it takes into consideration only the connectivity structure of the network. Static Analysis serves to observe what happens to the network's structure when components are taken away one by one, and ignores the dynamic changes in flows that could be produced during normal operation. This simplification brings as a positive feature the possibility of generalization of results to all kind of networks sharing similar structure. In this case, the failure of a component basically can only influence its very next neighborhood. Despite not being the best test to assess a power grid's robustness, static analysis can show a kind of minimal expected effect of failures over an entire system, and gives an general idea about the robustness of this last.

### **European Power Grid (EPG)**

Robustness behavior of networks having power law distribution of its degree coefficients, are known to present a

strong dependence on whether the loss of nodes is done randomly or selectively following their degree index.

Authors of [56] claim that this quality is observed also in electric power grids, in particular for the European Power Grid, even if this type of networks has not a power law distribution, but an exponential one:  $P(k) = c e^{-k/d}$ , (with  $d = 1.81$  and  $c = .7$  for the EPG.)

### 4.3.2 Static Robustness and SCA

SCA can be performed considering a sequence of nodes to be taken apart from the grid, in principle one by one, forming a sequence. Two ways of setting such sequences of nodes has been considered, namely:

- RANDOM selection of nodes, which are considered as representing accidental events perturbing the network and...
- Selection of nodes depending on some topological measure. This way of choosing the nodes is often used to simulate intentional attacks to the networks and, is therefore called "Selective Attack".

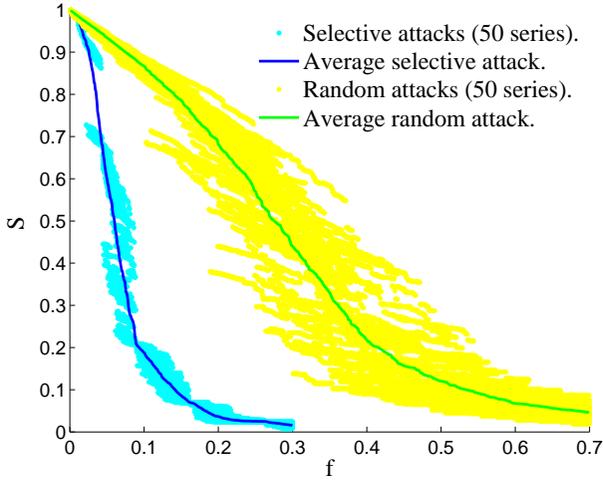
Authors of [56] performed static robustness analysis on the EPG and its subnets, using random loss of nodes as well as selective attacks following the degree index of nodes, in descending order.

Here, in figure 4.6, the results of the two processes are shown, making evident the more strong effect of the "degree coefficient" based attack. The variable on the horizontal axis,  $f$ , is the fraction of nodes taken apart from the network; and the variable on the vertical axis,  $S$ , is the relative size of the principal network component after the

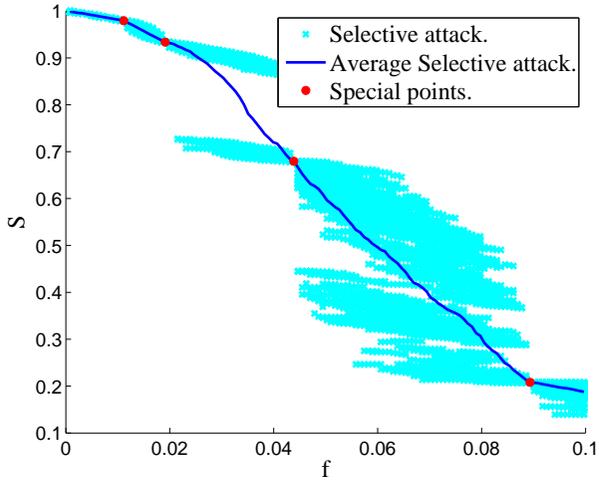
failures, i.e. the ratio between the number of nodes of the bigger remainder island and the original number of nodes of the grid.

A thing to note from the figure is the presence of some especial points for the sequences of "selective attacks". On this points, a common value of  $S$  for all the sequences is observed, (see Figure 4.7, for example at  $f=0.011$ ,  $0.019$  and  $0.044$ ). This detail can be explained realizing that: from the start of each sequence up to this especial points, the fallen nodes contained in all the sequences are exactly the same, corresponding to degree coefficients from the absolute maximum down to a specific value belonging to the concentration points. For example for  $f=0.011$ , all the nodes with  $k=13, 12...9$  were suppressed from the network, and the structure of the grid at this point could not have more than a unique value for  $S$  ( $=0.979$ ). Between each pair of this special points, all the nodes considered have exactly the same degree coefficient. So, many variations in the order in which those nodes are eliminated from the network can be made without altering the degree coefficient ordering. This possibility of choosing among the different permutations of nodes with the same degree index, is what allows the existence of many sequences to be used for attacking the network.

The advantage of using degree coefficient for atomizing the network can be thought as follows: if a node with high degree is taken apart from the grid, this implies a bigger chance of separating islands associated to some of its neighbors.



**Figure 4.6:** Static Tolerance against random and selective attacks.



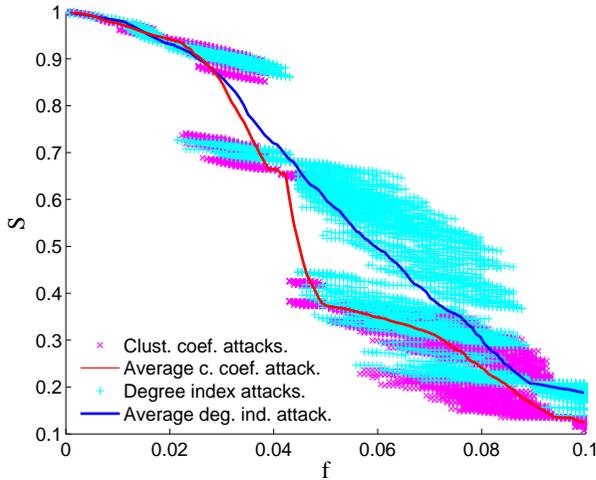
**Figure 4.7:** Static Tolerance against selective attacks.

**Static Robustness and clustering coefficient**

If adjacent nodes to a reference one are interconnected among each other, one can guess that a lesser isolation of distant parts would be produced. But interconnection between neighbors of a node calls for consideration of the clustering coefficient, (section 3.1.3). That is, if the cluster coefficient of a node is high, the isolation of its neighbors would be weak once it is removed from the network. Also, a low clustering coefficient implies scarce interconnection among the surrounding nodes, which give them a high chance of getting separated if the reference node is taken apart. Following this idea, a new experiment was carried out using the clustering coefficient to sort the nodes before starting their elimination from the network. This time, the best direction for ordering the nodes was the ascending one.

A comparison of attacks using degree coefficient and clustering coefficient is shown in Figure 4.8, where a slight superiority of the second sequences can be seen, (in magenta).

Although for low  $f$  there is some superposition of the outcomes from the two series of sorted sequences, the average values is in general better for attacks using the ascending cluster coefficient order (red line). The attacks using degree index displays a bigger variance and, its average trend (visible as the blue line) is above the corresponding to the clustering coefficient.



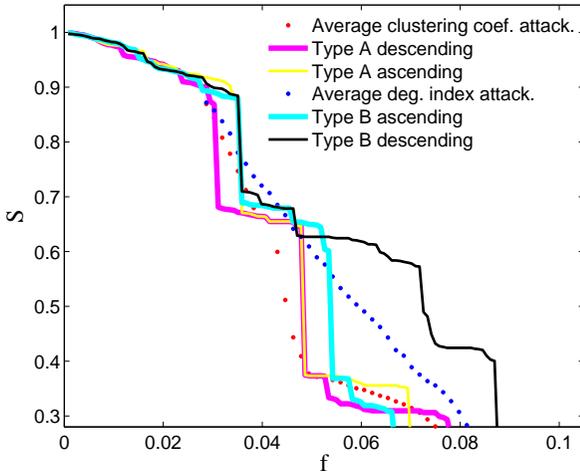
**Figure 4.8:** Degree coefficient vs. Clustering coefficient, 150 sequences.

### 4.3.3 Static Robustness Analysis using a Combination of Topological Indices

In the previous section the presence of many different sequences of nodes, all satisfying the same ordering regarding a topological coefficient has been mentioned. This various sequences show segments in which all nodes have the same value for the topological coefficient of interest. At their time, those segments of the sequences are also susceptible of being reordered, for example following a different topological coefficient.

Static contingency analysis has been performed using this double ordering for the EPG, using two different types of sequences:

- "A" Sequences of nodes: defined here as sequences with a primary ordering according to the ascending



**Figure 4.9:** Static Analysis using double ordered sequences for EPG.

clustering coefficient, plus an interior secondary ordering following the degree coefficient of nodes.

- "B" Sequences: defined as sequences with a primary ordering following the descending degree index, plus a secondary internal clustering-coefficient ordering.

As the second (internal) ordering can be done in ascending or descending direction, one instance in each direction was done for both sequences types A and, B. The outcome of the runs can be seen on Figure 4.9 where also the average values from Figure 4.8 are included to be serve as reference (dotted lines).

First to mention is that depending on whether the internal ordering is done in the descending or ascending direction, the results obtained after the attack shows a clear difference in the vertical variable  $S$  in almost all the

range of  $f$ . This is a clue indicating a real significance or usefulness of internal ordering. The most interesting directions of internal orderings, as could be expected, are "ascending" for the clustering coefficient inside type  $B$  sequences (cyan line); and "descending" for the degree coefficient inside the type  $A$  sequence (magenta line). The winner seem to be this last one, but it is convenient to make a more objective evaluation. So, a comparison with the sequences from the two previous sections, which follow only a primary ordering, is shown in figure 4.10.

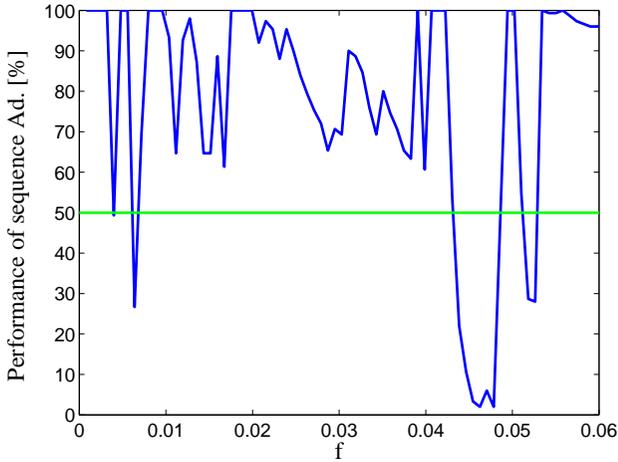
#### 4.3.4 Measuring performance of Static Robustness Assessment

There are many "simple ordered" sequences to compare with just one "double ordered". The measure of performance presented here consist in counting how many instances  $j$  among  $n$  sequences with simple clustering coefficient ordering ( $CCO$ ) are worse than the type  $A$  "interior descending" sequence ( $Ad$ ). It is "worse" in the sense of producing less damage to the network, that is a higher  $S$ . This performance ( $P_{Ad}$ ) of the sequence  $Ad$  is calculated as:

$$P_{Ad}(f) = 1/n \sum_j^n I_j$$

$$\text{with } I_j = \begin{cases} 1 & \text{if } S_{CCO_j}(f) - S_{Ad}(f) \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

So, from Figure 4.10 in the zone of  $f \in [0; 0.043]$ , selective attack using the sequence of nodes  $Ad$  is better or equal to more than a half (50%) of the  $CCO$  possible instances. Sequence  $Ad$  is clearly advantageous, since



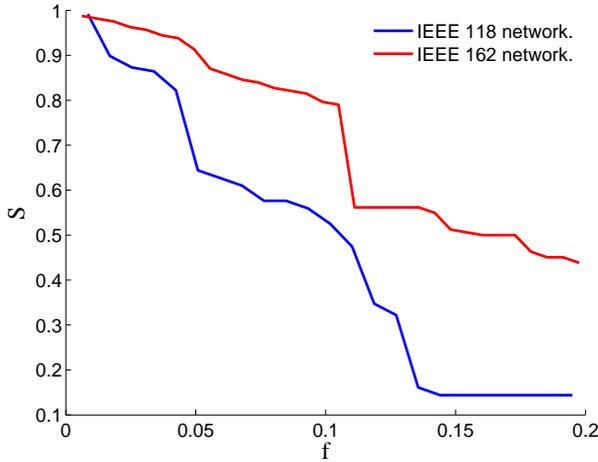
**Figure 4.10:** Performance of selective attack using double ordered sequence  $Ad$  for EPG.

it is surely good enough from a practical point of view: the fraction of the network which is separated from the principal component is around 34%. Any real power grid loosing such a portion of its nodes is clearly in a major blackout situation.

### 4.3.5 Results for other power networks

The satisfactory performance of applying sequence  $Ad$  to selectively attack EPG, is clearly not a general result. Since an analytical justification of the results is lack, at least qualitative result on other networks is necessary in order to not consider the method just a coincidence or a quality of EPG. So, the method has been applied on the "IEEE power system test cases 118, and 162 bus" [43].

Result for this two networks (shown on Figures 4.11 and 4.12) are compatible with those for EPG, indicating

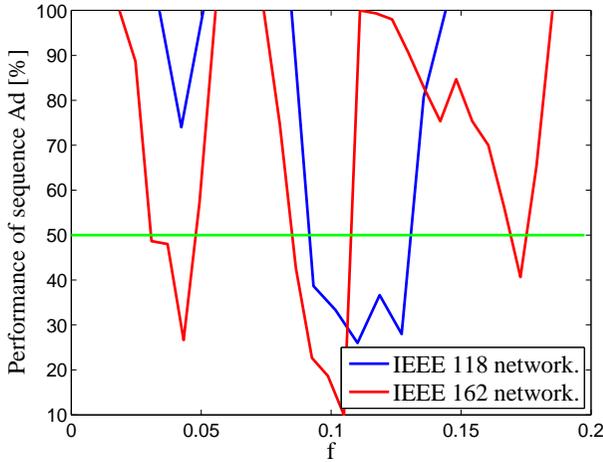


**Figure 4.11:** Size of largest connected component for networks IEEE 118 and IEEE 162 when subject to selective attack with sequences of nodes double ordered, "Ad".

the advantage of sequences like Ad (with primary ascending clustering-coefficient ordering and, interior descending degree coefficient ordering). From an attacker point of view, taking apart from the network the double ordered nodes is most of the times better than using sequences ordered with just a single coefficient.

#### 4.3.6 Third level of ordering for Static Analysis realization

As the use of double ordering showed a significant influence in the outcome of selective attacks, the idea of introducing one further depth of ordering has emerged. In this case, the third coefficient considered was a kind of "degree index of second level", calculated as the quantity of nodes with distance equal to 2 from the reference one.



**Figure 4.12:** Performance of selective attacks using node's sequences "Ad" for networks IEEE 118 and, IEEE 162.

Unfortunately, the sequences of nodes using this three-deep ordering had no practical influence on the outcome of  $S$ .

### 4.3.7 Usefulness of Combination of indices for Static Robustness Analysis

The use of degree index had been adopted to explore the static robustness of a power grid. Here, we have seen that such technique of selective attack can be improved by the use of clustering coefficient in place of degree index and further enhanced by applying an internal second depth ordering, in descending direction, following the degree index. This type of node ranking to implement selective attacks probably is not suitable for networks with degree distributions with insufficient dispersion, as in the case of

random networks. On the other hand, may be, it is worth testing the idea on "power law network", which show some dispersion in degree index.

(More on this topic is addressed in chapter 5.3).

# Discussion and Conclusions

## 5.1 On stress and dispatch policies

In the section (4.1), objective evidence was presented to support the simple statement: "Doing the grid safer is also more expensive". Also, from a standpoint considering "robustness indices" it can be said that in that section an index for measuring the stress of the grid,  $\gamma$ , has been defined using the transmission capacity as a reference. Taking as a base the dispatch policies used, and combining them with "stress", a qualitative estimation can be expressed about how risky is the grid operation. A strong quantitative indicator is lack, in part because a more extensive sets of BO simulations should be carried out first of being able to put that qualitative estimation as a number.

When talking about BO, it is known that for example, they are more likely to occur at certain times of the year due to weather conditions. In a similar, but much deterministic way, BOs are more likely to occur when

using certain dispatch policies. The dispatch policies seen in this thesis, have been evaluated statistically after producing a set of simulated BOs. None of them provide a single number telling how much risk of BO's there is at a given time; but each dispatch policy shows a strong trend. This knowledge could be advantageously used for automatic control systems to anticipate threatening situations, or reduce BOs impact.

## 5.2 On OSF index

The new topological index, OSF, presented on section 4.2 works effectively in conjunction with electrical betweenness, EB, in identifying nodes that are best suited to host generation devices. The experiments were carried out supposing all buses free to accept generators. It is expected that the enhancement in finding god nodes for generation remain mostly unchanged in case of working also with some fixed generators, even if the experiments were carried out supposing no fixed one. This is stated considering that the groups of nodes to run as generation sites were selected randomly from some pool of candidates. In the case of using some centralized generators, the performance of combining OSF and EB index could experiment some variation in intensity, but the general tendency should keep on if excluding those nodes from the candidate pools.

---

## **5.3 On combination of indices for Static Robustness Analysis**

The static contingency analyses done in section 4.3 show that the combination of degree index and clustering coefficient devised here can improve the selection of nodes to realize a selective attack over a network. (Conversely, the information provided is equally useful for defense purposes).

Clustering and degree coefficients are local topological measures, which makes them relatively appealing for being used by agents inside control areas of a grid. On the other hand, this static contingency analysis is not so well suited for power grids, since an electric system hardly could withstand a quite big number of component failures as used in the experiments. So, the applicability to power grids is somehow limited, but in any case the technique says something about the structural general robustness of a network. The methodology applied here could serve for comparing different networks (of any type) and determine which one is more resistant to attacks. The study also can serve as a basis for defining other indices capable of indicating robustness using attacks of lesser intensity.

## **5.4 Original Contribution**

The indices shown in this thesis, on sections 4.1 and 4.2 ("Economical Dispatch and BOs" and "Distributed Generation and BOs"), were presented as the following two conference papers:

- "Power Grid Dispatch Policies and Robustness to

Chain Failures", at 21<sup>st</sup> European Conference on Circuit Theory and Design, September 2013. Dresden, Germany.

- "Combined Topological Indices for Distributed Generation Planning", at 5<sup>th</sup> Innovative Smart Grid Technologies Conference, ISGT2014, February 2014. Washington D.C. USA.



---

# Bibliography

- [1] R. Baldick, B. Chowdhury, I. Dobson, D. Zhaoyang et.al. (IEEE PES CAMS Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures). *Initial review of methods for cascading failure analysis in electric power transmission systems*. IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1-8. 2008.
- [2] D. E. Nye, *When The Lights Went Out: A History Of Blackouts In America*. The MIT Press, 2010.
- [3] A. Keane, L. Ochoa, C. Borges, G. Ault, A. Alarcon-Rodriguez, R. Currie, F. Pilo, C. Dent and G. Harrison. *State-of-the-Art Techniques and Challenges Ahead for Distributed Generation Planning and Optimization*. IEEE Transactions on Power Systems, Vol. 28, No. 2, pp. 1493-1502. May 2013.

- 
- [4] M. Amin and J. Stringer. *The Electric Power Grid: Today and Tomorrow*. MRS Bulletin, Vol. 33, No. 4, pp. 399-407, April 2008.
- [5] P. Barker and R. de Mello. *Determining the impact of distributed generation on power systems; part 1 radial distribution systems*. IEEE Power Engineering Society Summer Meeting, 2000. (Volume:3, pp. 1645-1656).
- [6] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, W. D'haeseleer. *Distributed generation: definition, benefits and issues*. Energy Policy, vol. 33, issue 6, pp. 787-798, 2005.
- [7] H. Gharavi, R. Ghafurian. *Smart grid: the electric energy System of the future*. Proceedings of the IEEE, Volume: 99 , Issue: 6, pp. 917-921. 2011.
- [8] X. Chen, H. Dinh and B. Wang, *Cascading failures in smart grid - benefits of distributed generation*, in Proc. of 1st IEEE International Conference on Smart Grid Communications, pp. 73-78. 2010.
- [9] D. E. Newman, B. A. Carreras, M. Kirchner and I. Dobson. *The impact of distributed generation on power transmission grid dynamics*. 44rd Hawaii International Conference on System Science (HICSS), January 2011, Kauai, Hawaii, pp. 1-8.
- [10] N. Cai, and J. Mitra. *A Decentralized Control Architecture for a Microgrid with Power Electronic Interfaces*. North American Power Symposium (NAPS), 2010, pp. 1-8.

- [11] P.Hines, J. Apt, H. Liao, and S. Talukdar. *The frequency of large blackouts in the United States electrical transmission system: an empirical study*. Second Carnegie Mellon Conference in Monitoring, Sensing, Software and Its Valuation for the Changing Electric Power Industry. Pittsburgh, PA, January 2006.
- [12] A. Mittal, J. Hazra, N. Jain, V. Goyal, D. Seetharam, and Y. Sabharwal. *Real Time Contingency Analysis for Power Grids*. Euro-Par 2011 Parallel Processing Lecture Notes in Computer Science, LNCS 6853, part II, pp. 303-315. 2011.
- [13] B. Carreras, D. Newman, I. Dobson, and A. Poole. *Evidence for Self-Organized Criticality in a Time Series of Electric Power System Blackouts*. IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 51, No. 9, pp. 1733-1740, September 2004.
- [14] D. Cajueiro and R. Andrade. *Controlling self-organized criticality in Complex networks*. Eur. Phys. J. B 77, pp. 291-296. (2010).
- [15] C. Liang, W. Liu, J. Liang, Z. Chen. *The Influences of Power Grid Structure on Self Organized Criticality*. International Conference on Power System Technology (POWERCON), pp. 1-6, 2010.
- [16] . B. Carreras, V. Lynch, I. Dobson and D. Newman. *Critical points and transitions in an electric power transmission model for cascading failure blackouts*. Chaos, Vol. 12, No. 4, 2002.

- [17] M. Schlöpfer and J. Shapiro. *Modeling Failure Propagation in Large-Scale Engineering Networks*. J. Zhou (Ed.): Complex 2, volume 5 of Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, page 2127-2138. Springer, (2009).
- [18] I. Dobson, B. A. Carreras, V. E. Lynch and D. E. Newman. *Complex systems analysis of series of blackouts: cascading failure, criticality, and self-organization*. CHAOS, 17(2), June 2007.
- [19] P. Hines, J. Apt and S. Talukdar. *Trends in the history of large blackouts in the United States*. 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. (pp. 1-8).
- [20] D. Kirschen and D. Nedic. *Consideration of hidden failures in security analysis*. 14th Power Systems Computation Conference (PSCC), Sevilla, June 2002.
- [21] G. Pagani and M. Aiello. *The Power Grid as a complex network: A survey*. Physica A 392, pp. 2688-2700. (2013).
- [22] P. Crucitti, V. Latora and M. Marchiori. *Model for cascading failures in complex networks*. PHYSICAL REVIEW E 69, 045104(R), 2004.
- [23] P. Crucitti, V. Latora and M. Marchiori. *A topological analysis of the Italian electric power grid*. Physica A 338 (2004), pp. 92-97.
- [24] E. Estrada, N. Hatano *Resistance Distance, Information Centrality, Node Vulnerability and Vibrations in*

- Complex Networks*. Chapter 2 in "Network Science Complexity in Nature and Technology", Springer London, 2010.
- [25] J. Casazza and F. Delea, *Understanding Electric Power Systems*. Wiley and Sons, 2003.
- [26] A. Motter. *Cascade Control and Defense in Complex Networks*. Physical Review Letters, Vol. 93, No. 9, 2004.
- [27] D. Kirschen, G. Strbac. *Why investments do not prevent blackouts*. The Electricity Journal, Volume 17, Issue 2, March 2004, pp. 29-36.
- [28] U.S. Federal Power Commission. *Prevention of Power Failures. Vol. II, Advisory Committee Report: Reliability of Electric Bulk Power Supply*. Washington, DC: U.S. Government Printing Office. June 1967.
- [29] Z. Huang, Y. Chen, J. Nieplocha. *Massive Contingency Analysis with High Performance Computing*. IEEE Power and Energy Society General Meeting 2009. (pp. 1-8).
- [30] V. Shrivastava, O. Rahi, V. Gupta, and J. Kuntal, *Optimal Placement Methods of Distributed Generation: A Review*. Proc. of the Intl. Conf. on Advances in Computer, Electronics and Electrical Engineering, 2012, pp. 466-475.
- [31] Y. Mao, F. Liu and S. Mei. *On the Topological Characteristics of Power Grids with Distributed Generation*. Proceedings of the 29th Chinese Control Conference, July 29-31, 2010, Beijing, China, pp. 4714-4720.

- [32] R. Albert, I. Albert and G. Nakarado. *Structural Vulnerability of the North American Power Grid*. Physical Review E; 69(2 Pt. 2), 2004. .
- [33] R. Albert and A. Barabasi. *Statistical mechanics of complex networks*. Reviews of Modern Physics, Vol. 74, January 2002
- [34] D. Watts and S. Strogatz. *Collective dynamics of small-world networks*. Nature, Vol. 393, 4 June 1998.
- [35] K. Wang, B. Zhang, Z. Zhang, X. Yin and B. Wang. *An electrical betweenness approach for vulnerability assessment of power grids considering the capacity of generators and load*. Physica A, 390(2011) pp. 4692-4701.
- [36] E. Bompard, D. Wu, F. Xue. *The Concept of betweenness in the analysis of power grid vulnerability*. Complexity in Engineering, 2010 (COMPENG '10, pp. 52-54).
- [37] Z. Wang, A. Scaglione, R.J. Thomas. *Electrical Centrality Measures for Electric Power Grid vulnerability analysis*. 49th IEEE Conference on Decision and Control (CDC), 2010, pp. 5792-5797.
- [38] H. Song, R. Dosano and B. Lee. *Power Grid Node And Line Delta Centrality Measures For Selection Of Critical Lines In Terms Of Blackouts With Cascading Failures*. International Journal of Innovative Computing, Information and Control, Volume 7, No. 3, 2011, pp. 1321-1330.

- [39] IEEE Power & Energy Society. *1366-2012 IEEE Guide for Electric Power Distribution Reliability Indices*. 2012.
- [40] Energy department of USA. *Energy policy act 2005, sec. 1234*. 2005. Available online: <http://www.gpo.gov/fdsys/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf>
- [41] United States Department of Energy, *The value of economic dispatch a report to congress pursuant to section 1234 of the Policy Act 2005*. Nov. 2005. Available online: <http://energy.gov/oe/downloads/value-economic-dispatch-report-congress-pursuant-section-1234-energy-policy-act-2005>
- [42] M. Bhaskar, M. Srinivas and S. Maheswarapu, *Security constraint optimal power flow (SCOPF) - A comprehensive survey*, Global Journal of Technology and optimization, Vol. 2 pp. 11-20. 2011.
- [43] University of Washington. *Power Systems Test Case Archive*. Available online: <http://www.ee.washington.edu/research/pstca/>
- [44] V. Kazakov and A. M. Tsirlin *Optimal Dispatch in Electricity Markets*. Quantitative finance Research Center. Univ. of Technology Sydney. Research paper 206. 2007.
- [45] S. Mukherjee, A. Recio and C. Douligieris, *Optimal Power Flow By Linear Programming Based Optimization*, IEEE. Proc. Southeastcon '92, vol.2 pp. 527-529. 1992.

- [46] A. Wood and B. Wollenberg , *Power generation, operation, and control*, Wiley & Sons, 1996.
- [47] K. Purchala, L. Meeus, D. Van Dommelen and R. Belmans, *Usefulness of DC power flow for active power flow analysis*, in proc. The 8th IEEE International Conference on AC and DC Power Transmission, pp. 58-62, 2006.
- [48] B. Carreras and V. Lynch, I. Dobson, D. Newman. *Complex dynamics of blackouts in power transmission systems*. Chaos vol. 14, No. 3, pp. 643-652, 2004.
- [49] J. Salmeron, K. Wood, and R. Baldick. *Analysis of Electric Grid Security Under Terrorist Threat*. IEEE Transactions on power systems, Vol. 19, No. 2, pp. 905-912 May 2004.
- [50] D. Pepyne *Topology And Cascading Line Outages in Power Grids* J. Syst. Sci. Syst. Eng. (Jun 2007, 16(2): pp. 202-221).
- [51] D. Shanno and R. Weil, *Linear programming with absolute-value functionals*. Operations Research, Vol. 19, No. 1, pp. 120-124. 1971.
- [52] A. Keane, L.F., C.L.T. Borges, G.W. Ault et. al. (Task Force on Distributed Generation Planning and Optimization). *State-of-the-art techniques and challenges ahead for distributed generation planning and optimization*. IEEE Transactions on Power Systems, vol. 28, No. 2, pp. 1493-1502, May 2013.
- [53] D. E. Newman, B. A. Carreras, M. Kirchner and I. Dobson. *The impact of distributed generation on*

- power transmission grid dynamics*. 44rd Hawaii International Conference on System Science (pp. 1-8). Kauai, Hawaii, January 2011.
- [54] M. Halappanavar, Y. Chen, R. Adolf, D. Haglin, Z. Huang, M. Rice. *Towards efficient N-x contingency selection using group betweenness centrality*. 2012 SC Companion: High Performance Computing, Networking Storage and Analysis (SCC), pp. 273-282.
- [55] T. Guler, G. Gross and M. Liu. *Generalized line outage distribution factors*. IEEE Trans. Power Systems, Vol. 22, No. 2, pp. 879-881, may 2007.
- [56] M. Rosas-Casals, S. Valverde and R. Solé. *Topological Vulnerability of the European Power Grid Under Errors and Attacks*. Int. J. of Bifurcation and Chaos. Vol. 17, No. 7, pp. 2465-2475, Jul. 2007.



# A Details of Power Flow Methods

(Most of this appendix is from [46]).

The power flow problem consist basically in the determination of bus voltage, phase and line currents, allowing the calculation of power flowing in each grid element. Although , Supplied and consumed power at each bus of the grid, are normally taken as boundary conditions for the problem. As a power grid is simply an electric network, being buses and lines the nodes and branches respectively, the starting point to formulate a solution is the matrix relation between voltages and current at each node (bus) as in equation A.1:

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1N} \\ \vdots & & \vdots & \\ Y_{N1} & Y_{N2} & \dots & Y_{NN} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_4 \end{bmatrix} \quad (\text{A.1})$$

Where I and E are the vectors of current and voltages on the N buses the network. "Y" is the admittance matrix

for the network, having its elements the following rule of formation:

- If a line exist from bus  $i$  to bus  $j$   
 $Y_{ij} = -y_{ij}$   
 being  $y_{ij}$  the admittance of the line between nodes  $i$  and  $j$ .
- And:  $Y_{ii} = \sum_j y_{ij} + y_{ig}$   
 with  $y_{ig}$  being the possible admittance from node  $i$  to ground, and the index  $j$  going over all lines connected to node  $i$ .

## A.1 Gauss-Seidel method

Another important equation, is the one expressing the net injection of power at a bus:

$$\frac{P_k - jQ_k}{E_k^*} = \sum_{j=1, j \neq k} Y_{jk} E_j + Y_{kk} E_k \quad (\text{A.2})$$

This is taken as a base for applying the Gauss-Seidel method and resolve bus voltages, and after them the power flows. The basic expression for the Gauss-Seidel method is then:

$$E_k^{(n)} = \frac{1}{Y_{kk}} \frac{P_k - jQ_k}{E_k^{(n-1)*}} - \frac{1}{Y_{kk}} \left[ \sum_{j < k} Y_{kj} E_j^{(n)} + \sum_{j > k} Y_{kj} E_j^{(n-1)} \right] \quad (\text{A.3})$$

## A.2 Newton-Raphson Method

For an single-valued-single-variable function  $S(x)$ , the Newton's method involves the idea of an error being driven to zero by making adjustments  $\Delta x$  to the independent

variable associated with the function. Suppose we wish to solve:

$$S = F(x)$$

In Newton's method, we pick a starting value of  $x$  and call it  $x_0$ . The error, ( $\epsilon$ ), is the difference between  $S$  and a linear approximation to it. Using the Taylor expansion for the function about  $x_0$ :

$$\begin{aligned} F(x_0 + \Delta x) &= F(x_0) + F'(x_0)\Delta x + \epsilon \\ \Delta S &= S(x_0 + \Delta x) - S(x_0) \approx F'(x_0)\Delta x \end{aligned}$$

so, an approximation for  $\Delta x$  is

$$\Delta x \approx h = \frac{\Delta S(x_0)}{F'(x_0)} \quad (\text{A.4})$$

And the solution for the initial equation,  $S = F(x)$ , is sought iteratively, changing the value of the independent variable as:

$$h = \frac{\Delta S(x^{(n)})}{F'(x^{(n)})} \quad (\text{A.5})$$

$$x^{(n+1)} = x^{(n)} - h \quad (\text{A.6})$$

with ( $n$ ) indicating the  $n$  - th iteration. The Newton-Raphson method applied to power flow calculation uses a Jacobian matrix in place of a first derivative, and as a base the expression of the power injected to each bus:

$$P_i + jQ_i = E_i I_i^*$$

where

$$I_i = \sum_{k=1}^N Y_{ik} E_k$$

and then

$$P_i + jQ_i = E_i \left( \sum_{k=1}^N Y_{ik} E_k \right)^* \quad (\text{A.7})$$

$$P_i + jQ_i = |E_i|^2 Y_{ii}^* + \sum_{k=1, k \neq i}^N Y_{ik}^* E_i E_k^*$$

As in the Gauss-Seidel method, a set of starting voltages is used to get things going. The  $P + jQ$  calculated is subtracted from the scheduled  $P + jQ$  at the bus, and the resulting errors are stored in a vector. As shown in the following, we will assume that the voltages are in polar coordinates and that we are going to adjust each voltage magnitude and phase angle as separate independent variables. Note that at this point, two equations are written for each bus: one for real power and one for reactive power. For each bus we have:

$$\Delta P_i = \sum_{k=1}^N \frac{\partial P_i}{\partial \Theta_k} \Delta \Theta_k + \sum_{k=1}^N \frac{\partial P_i}{\partial |E_k|} \Delta |E_k|$$

$$\Delta Q_i = \sum_{k=1}^N \frac{\partial Q_i}{\partial \Theta_k} \Delta \Theta_k + \sum_{k=1}^N \frac{\partial Q_i}{\partial |E_k|} \Delta |E_k|$$

All the terms can be arranged as follows

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{\partial P_1}{\partial \Theta_1} & \frac{\partial P_1}{\partial |E_1|} & \cdots \\ \frac{\partial Q_1}{\partial \Theta_1} & \frac{\partial Q_1}{\partial |E_1|} & \cdots \\ \vdots & \vdots & \vdots \end{bmatrix}}_{\text{Jacobian Matrix}} \begin{bmatrix} \Delta \Theta_1 \\ \Delta |E_1| \\ \vdots \end{bmatrix} \quad (\text{A.8})$$

The matrix in the right hand side, is the Jacobian matrix for the network. This starts with the equation for the real and reactive power at each bus. Remembering the equation A.7:

$$P_i + jQ_i = E_i \sum_{k=1}^N Y_{ik}^* E_k^*$$

which can be expanded as:

$$\begin{aligned}
 P_i + jQ_i &= E_i \sum_{k=1}^N |E_k| |E_k| (G_{ik} - jB_{ik}) e^{j(\Theta_i - \Theta_k)} \\
 &= \sum_{k=1}^N \{ |E_i| |E_k| [G_{ik} \cos(\Theta_i - \Theta_k) + B_{ik} \sin(\Theta_i - \Theta_k)] \\
 &\quad + j |E_i| |E_k| [G_{ik} \sin(\Theta_i - \Theta_k) - B_{ik} \cos(\Theta_i - \Theta_k)] \}
 \end{aligned}$$

where  $\Theta_i$ ,  $\Theta_k$  are the phase angles at buses  $i$  and  $k$ , respectively;  $|E_i|$  and  $|E_k|$  the bus voltage magnitudes respectively;  $G_{ik} + jB_{ik} = Y_{ik}$  is the  $ik$  term in the  $Y$  matrix of the power system. The general practice in solving power flows by Newton's method has been to use  $\frac{\Delta|E_i|}{|E_i|}$ , instead of simply  $\Delta|E_i|$ ; this simplifies the equations. The derivatives are:

$$\begin{aligned}
 \frac{\partial P_i}{\partial \Theta_k} &= |E_i| |E_k| [G_{ik} \sin(\Theta_i - \Theta_k) - B_{ik} \cos(\Theta_i - \Theta_k)] \\
 \frac{\partial P_i}{\frac{\partial |E_k|}{|E_k|}} &= |E_i| |E_k| [G_{ik} \cos(\Theta_i - \Theta_k) + B_{ik} \sin(\Theta_i - \Theta_k)] \\
 \frac{\partial Q_i}{\partial \Theta_k} &= -|E_i| |E_k| [G_{ik} \cos(\Theta_i - \Theta_k) + B_{ik} \sin(\Theta_i - \Theta_k)] \\
 \frac{\partial Q_i}{\frac{\partial |E_k|}{|E_k|}} &= |E_i| |E_k| [G_{ik} \sin(\Theta_i - \Theta_k) - B_{ik} \cos(\Theta_i - \Theta_k)]
 \end{aligned} \tag{A.9}$$

Equation A.8 now becomes:

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} = [J] \begin{bmatrix} \Delta \Theta_1 \\ \frac{\Delta|E_1|}{|E_1|} \\ \Delta \Theta_2 \\ \frac{\Delta|E_2|}{|E_2|} \\ \vdots \end{bmatrix} \tag{A.10}$$

also...

$$\begin{bmatrix} \Delta\Theta_1 \\ \frac{\Delta|E_1|}{|E_1|} \\ \Delta\Theta_2 \\ \frac{\Delta|E_2|}{|E_2|} \\ \vdots \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} \quad (\text{A.11})$$

So, as done using equations A.5 and A.6 in the case of an single-valued function; for the power flow problem an initial estimation is done for the independent variables  $E$  and  $\Theta$ , and iterative updating thereof is made using the  $-\Delta$ 's given by equation A.11.

### A.3 Decoupled Power Flow

Decoupled method consist in a simplification of the Newton-Raphson method in order to avoid the burden of resolving and inverting the Jacobian matrix en each iteration.

Starting with the terms in the Jacobian matrix (equations A.9) the following simplifications are made:

- Neglect any interaction between  $P_i$  and any  $|E_k|$  (it was observed by power system engineers that real power was little influenced by changes in voltage magnitude). Then, all the derivatives  $\frac{\partial P_i}{\partial |E_k|}$  will be considered to be zero.
- Neglect any interaction between  $Q_i$  and  $\Theta_i$ , (a similar observation to the above one was made on the insensitivity of reactive power to changes in phase angle). Then, all the derivatives  $\frac{\partial Q_i}{\partial \Theta_k}$  are also considered to be zero.

- Let  $\cos(\Theta_i - \Theta_k) \approx 1$  which is a good approximation since  $(\Theta_i - \Theta_k)$  is usually small.
- Assume that  $G_{ik} \sin(\Theta_i - \Theta_k) \ll B_{ik}$
- Assume that  $Q_i \ll B_{ii}|E_i|^2$

This leaves the derivatives as:

$$\frac{\partial P_i}{\partial \Theta_k} = -|E_i||E_k|B_{ik} \quad (\text{A.12})$$

$$\frac{\partial Q_i}{\left(\frac{\partial |E_k|}{|E_k|}\right)} = -|E_i||E_k|B_{ik} \quad (\text{A.13})$$

If we now write the power flow adjustment equations as:

$$\Delta P_i = \frac{\partial P_i}{\partial \Theta_k} \Delta \Theta_k \quad (\text{A.14})$$

$$\Delta Q_i = \frac{\partial Q_i}{\left(\frac{\partial |E_k|}{|E_k|}\right)} \frac{\Delta |E_k|}{|E_k|} \quad (\text{A.15})$$

Then, substituting equations A.12 in A.14 and A.13 in A.15 we obtain:

$$\Delta P_i = -|E_i||E_k|B_{ik}\Delta\Theta_k \quad (\text{A.16})$$

$$\Delta Q_i = -|E_i||E_k|B_{ik} \frac{\Delta |E_k|}{|E_k|} \quad (\text{A.17})$$

Further simplification can then be made:

- Divide eqs. A.16 and A.17 by  $|E_i|$ .
- Assume  $|E_k| \approx 1$  in eq. A.16.

which results in:

$$\frac{\Delta P_i}{|E_i|} = -B_{ik}\Delta\Theta_k \quad (\text{A.18})$$

$$\frac{\Delta Q_i}{|E_i|} = -B_{ik}\Delta |E_k| \quad (\text{A.19})$$

And these lead to the following two matrix equations:

$$\begin{bmatrix} \frac{\Delta P_1}{|E_1|} \\ \frac{\Delta P_2}{|E_2|} \\ \vdots \end{bmatrix} = \begin{bmatrix} -B_{11} & -B_{12} & \dots \\ -B_{21} & -B_{22} & \dots \\ \vdots & & \end{bmatrix} \begin{bmatrix} \Delta|\Theta_1| \\ \Delta|\Theta_2| \\ \vdots \end{bmatrix} \quad (\text{A.20})$$

$$\begin{bmatrix} \frac{\Delta Q_1}{|E_1|} \\ \frac{\Delta Q_2}{|E_2|} \\ \vdots \end{bmatrix} = \begin{bmatrix} -B_{11} & -B_{12} & \dots \\ -B_{21} & -B_{22} & \dots \\ \vdots & & \end{bmatrix} \begin{bmatrix} \Delta|E_1| \\ \Delta|E_2| \\ \vdots \end{bmatrix} \quad (\text{A.21})$$

Note that both eqs. A.20 and A.21 use the same matrix. Further simplification can be done in the  $\Delta P$ - $\Delta\Theta$  relationship of eq. A.20:

- Assume  $r_{ik} \ll x_{ik}$ ; this changes  $-B_{ik}$  to  $-1/x_{ik}$ .
- Eliminate all shunt reactances to ground.
- Eliminate all Shunt to ground which arise from autotransformers.

Simplifying the  $\Delta Q$ - $\Delta|E|$  relationship of eq. A.21:

- Omit all effects from phase shift transformers. The resulting equations are:

$$\begin{bmatrix} \frac{\Delta P_1}{|E_1|} \\ \frac{\Delta P_2}{|E_2|} \\ \vdots \end{bmatrix} = [B'] \begin{bmatrix} \Delta\Theta_1 \\ \Delta\Theta_2 \\ \vdots \end{bmatrix} \quad (\text{A.22})$$

$$\begin{bmatrix} \frac{\Delta Q_1}{|E_1|} \\ \frac{\Delta Q_2}{|E_2|} \\ \vdots \end{bmatrix} = [B''] \begin{bmatrix} \Delta|E_1| \\ \Delta|E_2| \\ \vdots \end{bmatrix} \quad (\text{A.23})$$

where the terms in the matrices are:

$$B'_{ik} = -\frac{1}{x_{ik}}, \text{ assuming a branch from } i \text{ to } k \text{ (zero otherwise)}$$

$$B'_{ii} = \sum_{k=1}^N \frac{1}{x_{ik}}$$

$$B''_{ik} = -B_{ik} = -\frac{X_{ik}}{r_{ik}^2 + X_{ik}^2}$$
$$B''_{ik} = \sum_{k=1}^N -B_{ik}$$

As  $B'_{ik}$  and  $B''_{ik}$  are constants they can be calculated once and no more updated, different from what is required for the Newton method.

-----