UNIVERSIDADE DE
COIMBRA

João Filipe Beja Ferreira

SMART GRIDS
ANÁLISE DE FALHAS EM CASCATA

VOLUME 1

Dissertação no âmbito do Mestrado Integrado em Engenharia Eletrotécnica e de Computadores do ramo de Telecomunicações orientada pela Professora Doutora Rita Cristina Girão Coelho da Silva e apresentada ao Departamento de Engenharia Eletrotécnica.

Setembro de 2018

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SMART GRIDS
Analyzing Cascading Failures

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Dissertation in the scope of the Integrated Master in Electrical and Computer Engineering of the Telecommunications branch guided by Ph.D. Professor Rita Cristina Girão Coelho da Silva and presented to the Department of Electrical and Computer Engineering.

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Resumo

A rede elétrica tornou-se extremamente complexa e depende cada vez mais das redes de comunicação, às quais está interligada. Rede elétrica inteligente é o termo usado para referir essas redes onde a geração e a distribuição elétrica estão totalmente interligadas, instrumentadas, automatizadas e controladas. Estas propriedades tornam estes sistemas confiáveis, eficientes, seguros e económicos.

Uma forte interdependência entre as redes de energia e de comunicações proporciona comunicações bidirecionais e tecnologias de informação através de todo o sistema, permitindo assim monitorização em tempo real dos dispositivos, com grande volume de dados a serem recolhidos de medidores inteligentes e outros sensores da rede, o que permite a tomada de decisões quase instantâneas de modo a manter o seu adequado funcionamento. Embora estes desenvolvimentos tenham atribuído inteligência à rede, devido à sua natureza complexa, há diversas vulnerabilidades nestes sistemas, que são um grande desafio a superar.

Como as redes elétricas estão sujeitas a muitos tipos de riscos que podem colocar em causa o seu adequado funcionamento, é de grande importância garantir melhorias que levem a uma rede robusta e confiável. Análises pós-falha de algumas grandes falhas energéticas registadas nos últimos anos mostraram que em algumas situações a causa do problema foi uma falha de um único elemento da rede, que desencadeou uma sucessão de falhas em cascata que resultaram em grandes apagões que afetaram milhões de pessoas.

O foco desta dissertação será a análise e a simulação de falhas em cascata numa rede interdependente de energia e comunicações. Ao longo deste trabalho, os componentes e arquitetura das redes serão apresentados e discutidos. A abordagem baseia-se na interação entre as duas redes, onde um modelo foi proposto para capturar os efeitos das falhas em diferentes componentes das redes e o impacto dessas falhas, devido à interdependência entre elementos das duas redes.

Palavras-Chave: Rede elétrica inteligente, Falhas em cascata, Elementos críticos, Redes de comunicação, Interdependência

Abstract

The power grid became extremely complex and increasingly relying on communications network to which it is interconnected. Smart grid is the term used for this grid, where the electrical generation and distribution are fully networked, instrumented, automated and controlled. These properties make these systems reliable, efficient, secure and cost-effective.

A strong interdependency between the power and the communications networks provides bidirectional communications and information technologies across the entire power system, thus enabling a real-time monitoring of the devices, with volumes of data being collected from smart meters and other grid sensors, which allows near-instantaneous decisions in order to maintain its proper functioning. Although these deployments have given intelligence to the grid, due to their complex nature, there are several vulnerabilities on these systems which are a major challenge to overcome.

Since power grids are subject to many types of hazards that may jeopardize its proper functioning, it’s of great importance to ensure improvements leading to a reliable and robust grid. Post-failure analysis of some major power outages in recent years showed that the outages root cause was a failure of a single grid element, which triggered a succession of cascading failures which led to large blackouts affecting millions of people.

The focus of this dissertation will be the analysis and simulation of cascading failures in an interdependent network of power and communications. Throughout this work, the components and architecture of the grid are presented and discussed. The approach is based on the interaction between the two networks, where a model was proposed to capture the effect of failures in different network components and the impact of these failures, due to the interdependency between elements of the two networks.

Keywords: Smart grid, Cascading failures, Critical elements, Communication networks, Interdependency

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Abbreviations and Acronyms

DER	Distributed Energy Resources
DSEM	Demand Side Energy Management
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
MATLAB	MATrixLABoratory
N-R	Newton-Raphson
PF	Power Flow
P.U.	Per Unit

Chapter 1 – Introduction

This chapter presents the topics and scope of this work. Some background on smart grids and the motivation of this dissertation will be addressed, as well as the main goals. Lastly, the structure of this work will be presented.

1.1 Background and Motivation

Modern society and its economy depend heavily on critical infrastructures such as electricity, water, gas, oil, and telecommunications systems. Among them, the electric power system is particularly critical as most of the other infrastructures depend on it to ensure its management and operability [1].

The power grid didn't undergo significant changes during many decades regarding the electrical infrastructure. These systems have become obsolete and have proved to be inefficient for current needs, as energy demand increases from year to year. Governments have already become aware of existing problems and have started investing on the renovation of the actual grid, aiming at a more resilient, robust and reliable grid [2]. Environmental concerns have also been the focus of attention in recent years and systems are becoming increasingly environmentally friendly.

The smart grid concept emerges to overcome these problems of the traditional grids. Smart grids, as the name suggests, have brought intelligence to the grid, making it highly interactive and more distributed. This new generation grid can be viewed as a smarter version of the traditional power grid. It integrates an information and communication technology (ICT) network with the existing electrical system providing bidirectional information flow, allowing real-time controllability and monitoring of the system to improve the security, efficiency, resiliency and reliability of the network. It is worth noting the importance of these advances since they brought new features to the grid. Among them are the integration of distributed energy resources (DER), efficient demand side energy management (DSEM) and the dynamic optimization of grid operations, which revolutionized the way electricity is produced, delivered and consumed [3, 4]. A layered model of modern power systems is depicted in Fig. 1.1.1.

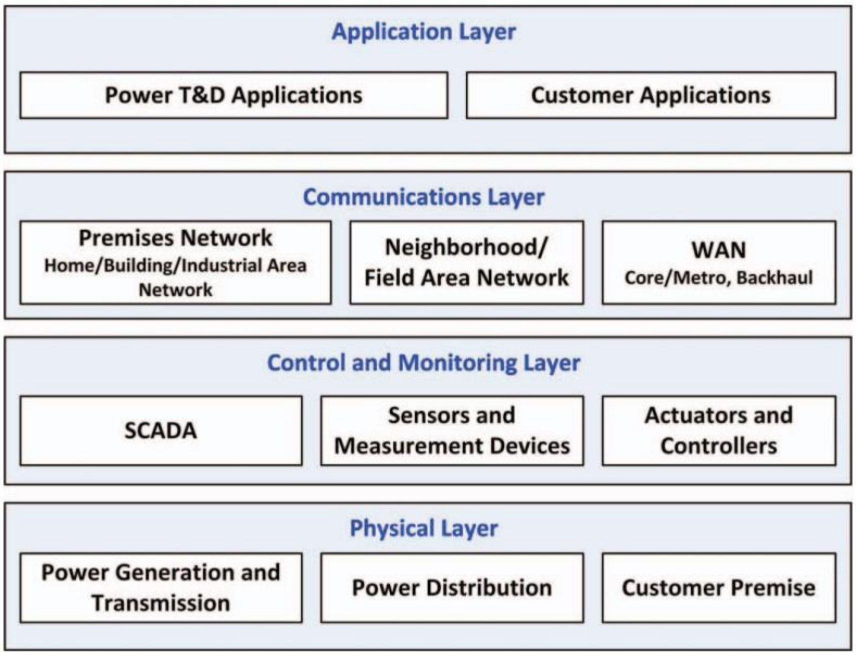


Fig. 1.1.1 - Layered model of modern power systems [4].

Despite all the benefits, the interdependency between the power and communication networks has also brought several issues to the grid, turning it more vulnerable and eventually less reliable [4]. In fact, the existence of failures in one of the networks may trigger failures in the other, since power nodes are controlled and managed by communication nodes, which in turn need the power supplied by the power nodes for its correct operation [5]. Faults in any of the networks may trigger cascading failure mechanisms with large scale effects [6].

Although in this work the focus is on cascading failures resulting from the interdependency of power and communication networks, these failures are also present in other types of interdependent networks. To the best of our knowledge, motivated by the blackout in Italy (2003), Buldyrev et al. [7], was the pioneer of the studies in cascading failures considering interdependent networks. Since then, many other studies regarding cascading failures in interdependent networks have been addressed. For more details about these studies, see [8] and references there in.

To clearly show how these cascades may affect the smart grid, Fig. 1.1.2 describes an example of a possible cascading failure caused by the interdependency of the power and communication networks. "A disruption in (1) causes edge failures (2) in the power grid, as well as node and edge failures (3) in the communication network. In this model when a node fails, the associated edges in both networks also fail" [9].

Recent blackouts, mainly caused by natural disasters, cyber-attacks and physical attacks, have exposed the susceptibility of the grids to these phenomena of cascading failures. These events threaten and compromise the proper functioning of the grid [10]. Motivated by the frequent occurrence of power outages in recent years, the focus of this dissertation will be on cascading failures analysis regarding the impacts of the interdependency between power grid and communication networks.

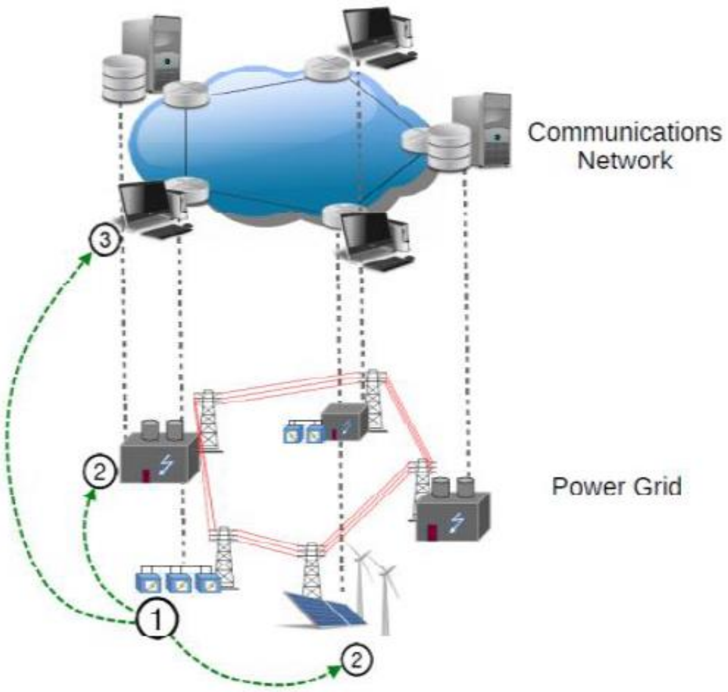


Fig. 1.1.2 – Interdependency between power and communication networks [9].

1.2 Goals

The main objective of this dissertation is to simulate the effects of cascading failures in smart grids. The deployed software was based on grid AC power flow dynamics taking into account the power line capacities in order to obtain coherent and close to reality results. The purpose of this software is to perform a steady state analysis of the grid when subjected to faults in the grid or in the ICT and understand the post initial failure impacts resulting from the interdependency of power and communication networks. Thus, it will be possible to analyse which components of the system will remain active or if a power outage occurs after the disturbances. Power flows and losses will also be calculated in order to characterize and understand the systems behavior.

1.3 Outline

Following this introduction, Chapter 2 will present an overview on cascading failures and catastrophic historical events, concluding with the related work resulting from the research community efforts. Chapter 3 will lay the foundations of the work and address the used methodology. In Chapter 4, the experimental results are exposed and Chapter 5 presents some conclusions about the developed work and some proposals for future work. Appendix I contains the schematic representations and data of the energy systems used in the work. Finally, in Appendix 2 more simulation results are presented.

Chapter 2 – State of the Art

2.1 Context

The interdependency of power and communication networks has several advantages, but it also presents several challenges. The two networks are very diverse in nature, with different operating and control procedures, which can be difficult to coordinate. If under normal operating conditions, the management of dependencies is already difficult, in case of failure, this management becomes even more problematic. Failure scenarios may be due to software failures, malfunction of components, cyber or physical attacks, accidents (natural or human-influenced), etc.

On August 2003, most of the Midwest and Northeastern of the United States and Ontario, Canada, experienced a blackout that affected about 50 million people [5]. The blackout started due to inadequate tree trimming which led to the failure of transmission lines in Ohio triggering a cascade of failures [11]. That same year, a short circuit in a transmission line of Switzerland triggered a cascading failure causing a blackout that covered almost the entire Italy and part of Southern Switzerland [12]. The shutdown of power stations led to failures in communications, which in turn led to the shutdown of more power stations [7]. On July 2012, more than 600 million people were affected by an enormous blackout in India. It was the biggest blackout in history regarding the number of people affected [13]. More recently, on December 2015, there was a cyber-attack on a Ukrainian power utility’s control system where a malicious actor took control of the system and started to open and close circuit breakers without authorization from the operator. The result was the loss of power for up to six hours, where approximately 225000 customers were affected [14]. Such calamities expose the vulnerabilities and susceptibilities of these infrastructures to attacks and failures that threaten their availability condition [10].

2.2 Related Work

The interconnection of the two networks (power and communications) entails enormous challenges regarding the system robustness and reliability. Many efforts have been made by the research community to deal with these challenges.

2.2.1 Modeling of Cascading Failures Propagation

Up to the seminal work by Buldyrev et al. [7], the researches regarding cascading failures were limited to single non-interacting networks. The authors of [7] proposed a model considering a ‘one-to-one’ interdependency of two networks and studied the effects of cascading failures in these networks.

Authors in [5] investigated cascading failures on interdependent networks through a model based on percolation theory. Their main goal was the estimation of the fraction of nodes that remain active after the cascade stops. In [15] a model to analyse the cascading effects on interdependent networks is also deployed. In this model, the heterogeneity of the structure of both networks is addressed and the interdependencies are differentiated as logical and physical interdependencies. A model was also deployed in [6], but it is not very close to reality since it disregards the power flow equations and also the power supply or demand. It focuses purely on the connectivity between power network components and communication network components, to capture the properties of interdependent networks. In [16] a more comprehensive model to analyse the dependency between two general networks was developed. In this work, a new centrality metric was proposed and the simulations conducted on three different types of network models revealed its powerfulness. More recently, authors in [17] developed a three-layer model to analyse the cascading effect phenomena on smart grids, and considered as third layer the human operator’s response.

2.2.2 Mitigation of Cascading Failures

Several strategies have been proposed to mitigate cascading failures, most of them focusing only on the effects on the power network and leaving aside the effects on the communications network. Authors in [18] suggested load reduction and islanding mechanisms combining distributed energy resources (DER) as mitigation strategies to limit the grid damage caused by cascading failures. A routing strategy aimed at the mitigation of cascading failures was proposed in [19]. The strategy is to assign weights to individual network links and define an adjustable parameter to control the weights. The flows and routing patterns are controlled by these weights. The presented results confirmed the effectiveness of the load redistribution. Parandehgheibi et al. [11] proposed a control policy to mitigate cascading failures. In a first approach, the non-avoidable failures that occur due to physical disconnections are identified. After the failure, the power is redistributed in a way that all the communication nodes are still being properly fed and no overload occurs in the power lines. Results from the analysis showed that the interdependent networks are more prone to failures than the isolated networks.

Some works regarding the mitigation of cascading failures and their effects on communication networks components were also done. In [20], the authors deployed an emergency control policy model to operate in interdependent power and communication networks. They used the emergency control to mitigate the failures in the power grid in the presence of a fully or partially operational communication network, targeting the maximization of the served load and the grid's stability.

Duan et al. [21] proposed a best effort broadcast algorithm where they guarantee that in case of a failure in a communication node, the messages are correctly delivered by means of alternative paths. To achieve this, the communication nodes analyse the cascading failures events and keep the information in a fully distributed manner. To establish those alternative paths called soft links, the routing tables are updated in case of failures. These updates are based on the information collected by the communication nodes when the cascading failures analysis is performed.

2.2.3 Identification of Critical Elements

The identification of critical elements in smart grids is very important, since they can have a great impact on the vulnerability of the systems. If the operability of a critical element is compromised, due to the interdependency of the networks, other elements in the same network and/or in the other network may be affected and stop their functions.

Regarding critical nodes, Crucitti et al. [22] developed a model to analyse the networks response to node removals. The model was based on the dynamical redistribution of flows triggered by an initial fault in a system component. The results showed that a failure in one single node is sufficient to compromise the entire network. In this work the authors did not consider the (N-1) contingency criterion, widely used by transmission system operators, which states that after a single outage of a transmission line, generator or a transformer, the grid shall continue to operate normally [23, 24].

Authors in [10] also tackle the problem of identifying critical elements, not on nodes, but on links. The survey shows how the interdependency of the power and communication networks deeply impacts the grid reliability. They developed a Mixed Integer Linear Programming model aiming to identify a set of available power and communication links, whose failure can trigger a cascading failure and compromise the entire system. Their approach is to quantify the system losses as a percentage of the initial served load. They proved that the smart grid vulnerability increases when these links are attacked.

Ruj et al. [25] studied the effect of targeted attacks in which the attacker selectively disrupts some communication nodes. The authors argue that the attacker is more likely to attack selected high degree nodes, instead of randomly attack. They compared targeted attacks, random attacks and a combination of both. The results show that targeted attacks can cause a huge network damage compared to random attacks, in which the network may still remain connected and work properly.

Chapter 3 – Interdependency Model

3.1 Power Network

A power grid comprises several buses, which are connected by transmission lines. Each transmission line is protected by the buses located at its two ends. Normally, this protection is made implementing current differential protection in these two buses, protecting the transmission line from faults [26]. A bus, in electrical systems context, is a node in which one or more transmission lines and one or more loads and generators are connected [27].

Differently from other type of networks, in power systems the energy flows satisfy Kirchhoff's laws. Thus, when a fault in a power grid occurs, the flows are redistributed to the rest of the grid, satisfying Kirchhoff's laws, and some elements can be overloaded leading to failure. For proper planning and operation of the power systems it is necessary to determine the dispatch schedule of generators in order to minimize the generation cost and, at the same time, satisfy the system limits [28]. Power flow (PF) analysis is indispensable to understand the power dynamics in the system. A steady state stability analysis will be performed to provide important and detailed information about the system for different operating conditions. Steady state stability can be defined as the capacity of a system to return to its original/previous state when subjected to disturbances [29].

PF analysis is undertaken to determine:

i) Voltages and phase angles at each bus;
ii) Active and reactive power at each bus;
iii) Line flows and losses;
iv) The effects in case of temporary losses regarding transmission capacities and generations on supplied loads;
v) Strategies to minimize generation and distribution costs.

Since the assumptions in linearized DC power flow models are based on a linearization of the AC power flow models, thus ignoring power losses, variations of voltage magnitudes and reactive power flows, which in turn make the model less realistic and can lead to overly optimistic cascading failures analysis [30], we opted for the AC power flow model.

To analyse the dynamics in power systems, the non-linear AC power flow model is presented in equation (1) where N is the number of power nodes (buses), P_k and Q_k represent the active and reactive power at bus k respectively, V_k and θ_k represent the voltage and phase at bus k respectively. G and B are, respectively, the transmission line conductance and susceptance [10].

$$P_k = \sum_{j=1}^{N} |V_k||V_j| \left(G_{kj}\cos(\theta_k - \theta_j) + B_{kj}\sin(\theta_k - \theta_j)\right) \quad (1a)$$

$$Q_k = \sum_{j=1}^{N} |V_k||V_j| \left(G_{kj}\sin(\theta_k - \theta_j) - B_{kj}\cos(\theta_k - \theta_j)\right) \quad (1b)$$

Our studies will be based on IEEE synthetic power grids which are fictitious test cases designed for studies of power systems, more specifically on IEEE 6-bus and IEEE 14-bus systems. The detailed characteristics of these systems are shown in the Appendix I. The main advantage of using these test cases is that they have characteristics close to real power grids [31].

To solve the non-linear AC power flow equations in order to obtain the load flow solution, the iterative mathematical method chosen was the conventional Newton-Raphson (NR) method. A simplified flowchart of a general iterative method applied to power systems is illustrated in Fig. 3.1.1. The NR method is widely used to solve non-linear equations, since it transforms the original non-linear equations into a sequence of linear equations and provides an approximate solution. The NR method converges fast and is more accurate when compared to other methods [32], and this was one of the main reasons for this choice. Although the NR method is the most robust power flow algorithm, some disadvantages can be pointed out. One of the main problems of the method, and common to all iterative methods, is that convergence is not guaranteed [31]. A stop criterion was applied, guaranteeing that if the method reaches the 100-th iteration without finding a solution within the specified tolerance, the method stops. An exclusive drawback of the NR method is the fact that the terms of the Jacobian matrix may have to be recalculated many times until the reach of the stop condition [27]. Many other factors can affect the method convergence when applied to power systems, such as problem conditioning, voltage stability characteristics, and the high sensitivity in the choice of initial values for variables.

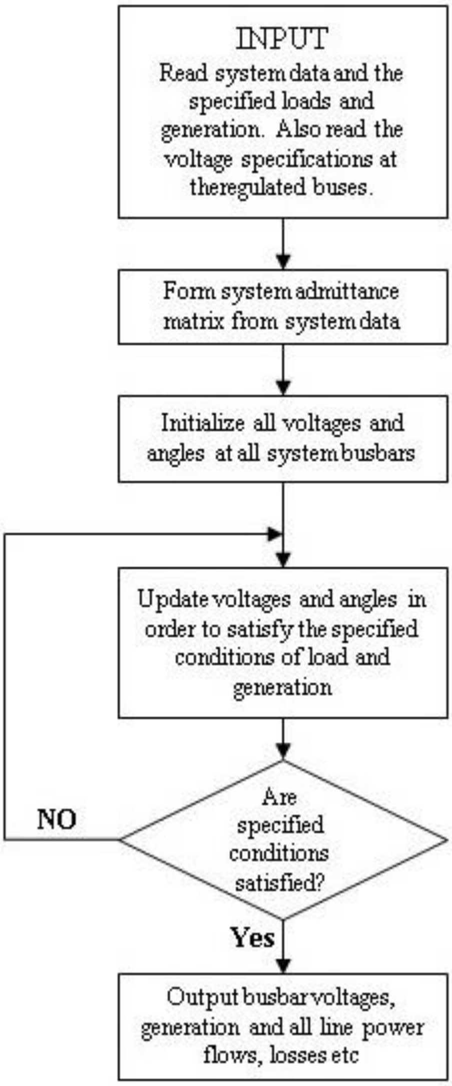


Fig. 3.1.1 - Simplified flowchart for application of an iterative method to power systems [27]

To implement the NR algorithm, some portions of code from [33] were used.

In power flow analysis, the buses are classified into 3 categories: Slack bus, generator bus and load bus. In our model, we protected the first one against failures since and all the grid losses are burdened on this bus. This bus is kept out of the iterative process and its power is only calculated at the end of the iterative process, when convergence is reached [34]. For more details about power flow analysis, see [34, 28, 27].

Since the capacity of the transmission lines are a critical factor on power systems stability, they cannot be ignored and must be part of the model. However, to the best of our knowledge, there is no available data regarding transmission lines capacity, for the networks considered in our tests. The tables containing the capacity data of the transmission lines can be found in Tables AI.3 and AI.6, included in Appendix I. We modeled those capacities as a tolerance over the stable apparent power values that flow in each line of the systems. By stable apparent power values we mean the apparent power values across the lines, when there are no system failures in the standard power systems. Since there are losses, for simplicity we chose the highest apparent power values that flow in each line. Those values were obtained after running the software without any failure as input.

3.2 Communication Network

The presence of communications in power grids is indispensable to their reliable and efficient operation [10]. Usually the communication infrastructure is implemented based on the topology of the power network. The methodology to the communication network infrastructure deployment is presented in this section.

The synthetic electric grids used in this work have detailed parameters for their components such as loads, generators, transmission lines and system topologies. However, none of them includes any communication structure.

To model the communication infrastructure, there are some initial interdependencies between the two networks that must be introduced. For interconnections between buses that have transformers, we consider these buses as belonging to the same substation since they are generally very close geographically, and only one node of communication is assigned to this substation. Only one communication link is assumed between two routers, even if the buses associated to them are connected by one (or more) transmission line(s) [26]. It is assumed that the capacities of data links are very high in order to satisfy the data flows demand.

We have established that the control center is directly connected to one of the routers with more communication links assigned. The power load demand for routers supplying was neglected because, in this context, these values are too small when compared to the other loads in the power system.

With these assumptions and methodology, the supporting communication infrastructure topology can be obtained based on the topology of the power grid transmission lines. For a better understanding of the practical application of these rules, the supporting communication infrastructures of the IEEE 6-bus and IEEE 14-bus systems are shown in Figures 3.2.1 and 3.2.2, respectively.

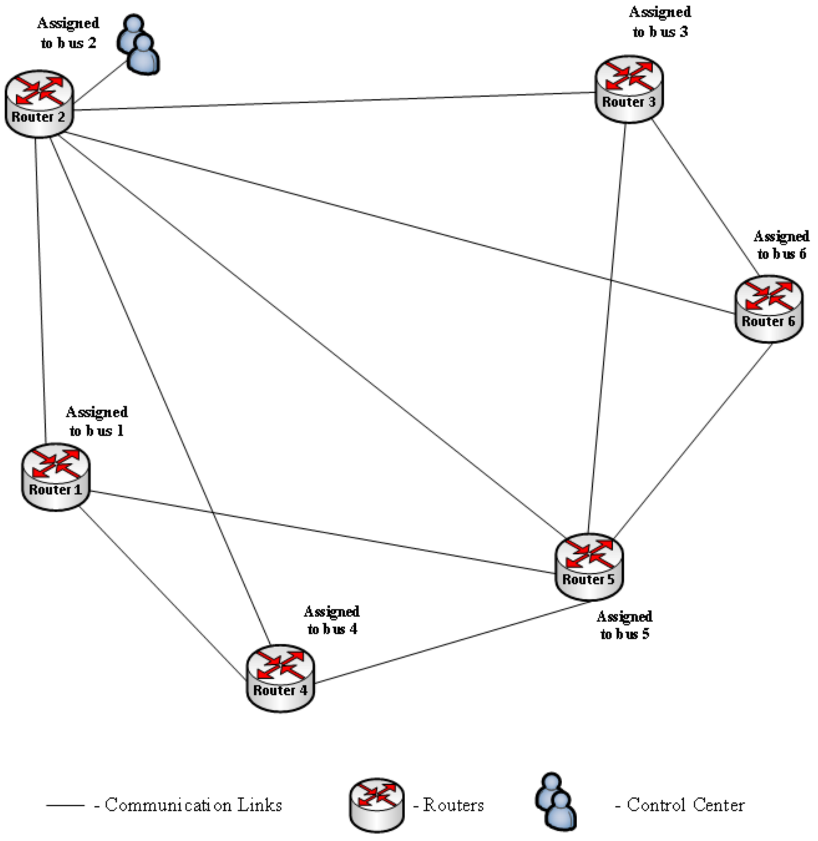


Fig. 3.2.1 – IEEE 6-bus system communication infrastructure topology

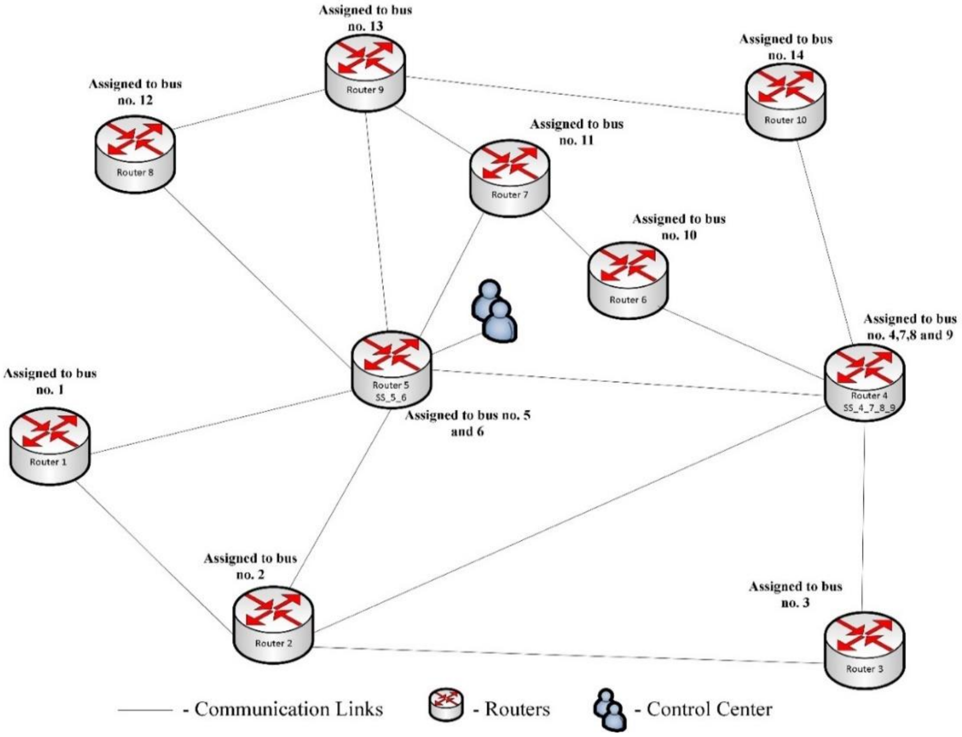


Fig. 3.2.2 – IEEE 14-bus system communication infrastructure topology (based on [26])

It should be noted that the control centers were placed near the router 2 assigned to bus no. 2 for the IEEE 6-bus system, and near the router 5 assigned to the buses 5 and 6 (at the substation denoted by SS_5_6) for the IEEE 14-bus system.

3.3 Interdependency between Power and Communication Network

After setting up the communication infrastructure, the interdependencies between the power and the communications networks have to be established. Power nodes depend on the communication nodes from which they receive the necessary data for an adequate system control and monitoring. Communication nodes depend on the power nodes from which they receive the necessary power to operate [15]. The presence of these interdependencies may accentuate the impacts of the failures [10].

In our model, the routers assigned to a substation can be power supplied by any of the buses in that substation. A router only fails if all of its supplying buses fail or all the communication links directly connected to it fail. Only one active connection is enough for the router to remain connected to the network without operating issues. A bus fails if all the transmission lines directly connected to it are overloaded or if its assigned router fails (i.e. loses all communications with the control center). This is a direct consequence of the interdependency between the two networks.

The deployed interdependent models applied to the IEEE 6-bus and IEEE 14-bus systems are depicted in Figures 3.3.1 and 3.3.2.

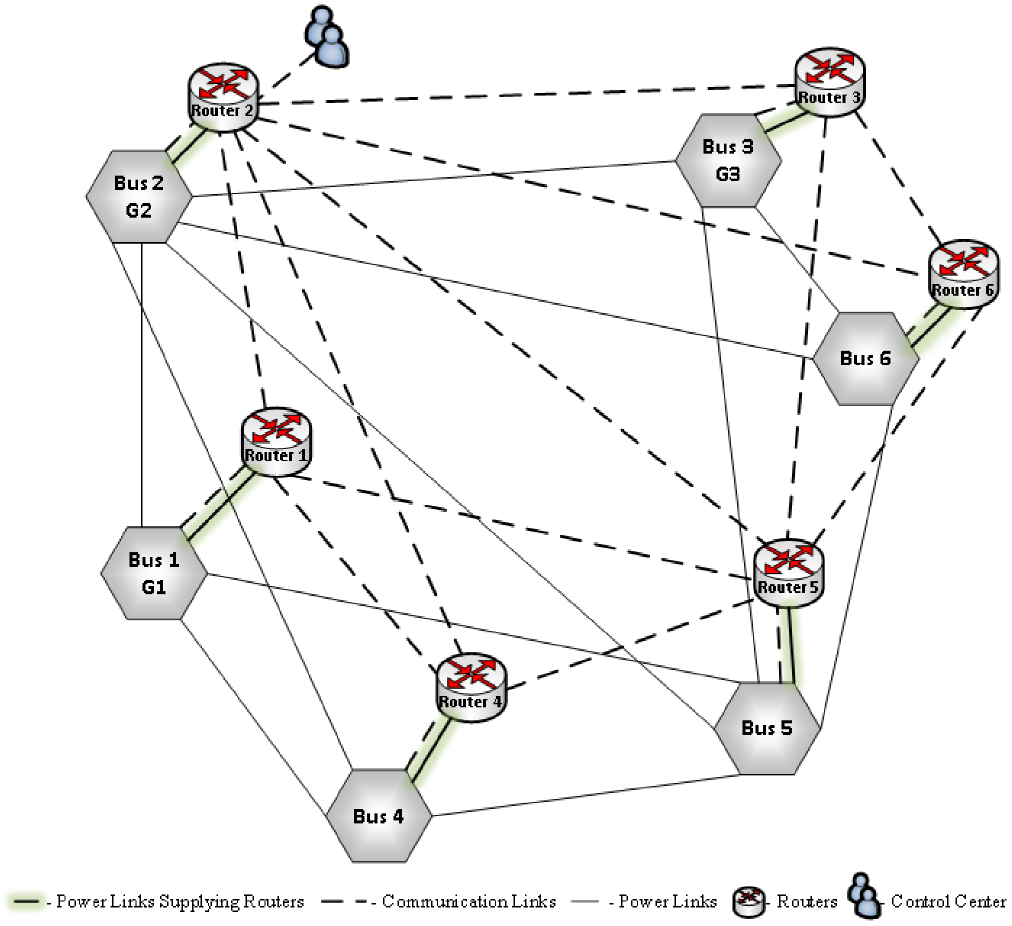


Fig. 3.3.1 – IEEE 6-bus system interdependent model infrastructure topology

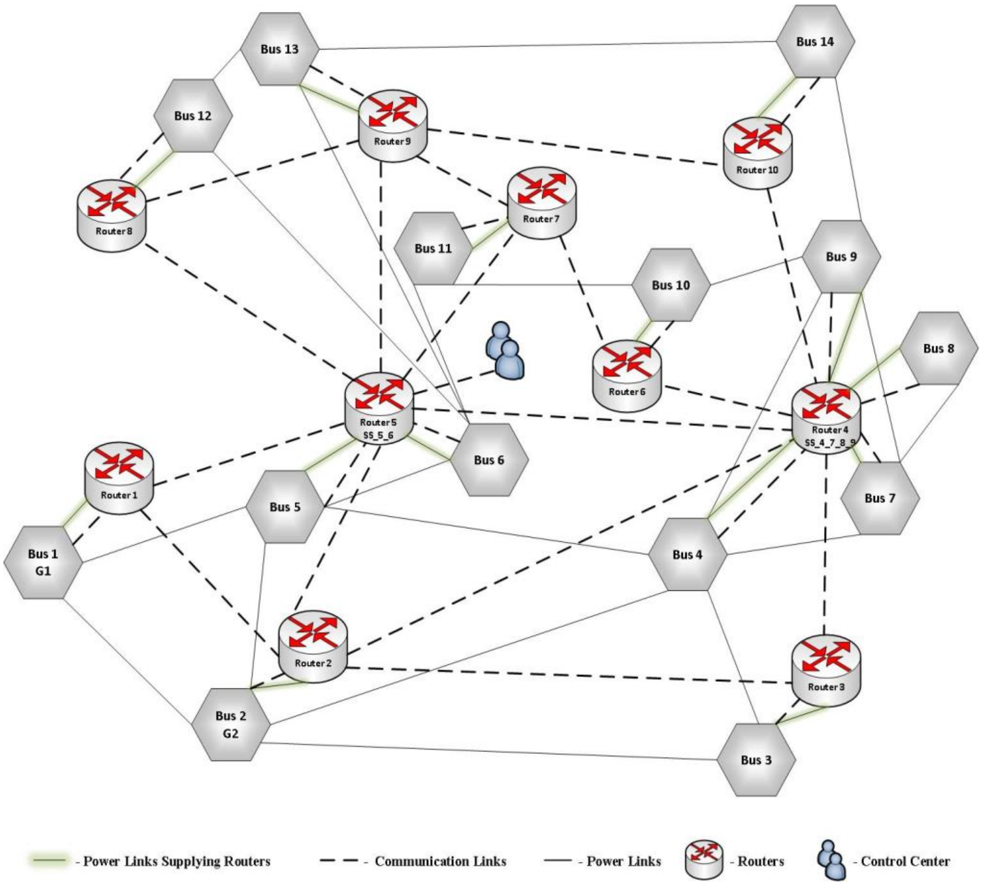


Fig. 3.3.2 – IEEE 14-bus system interdependent model infrastructure topology

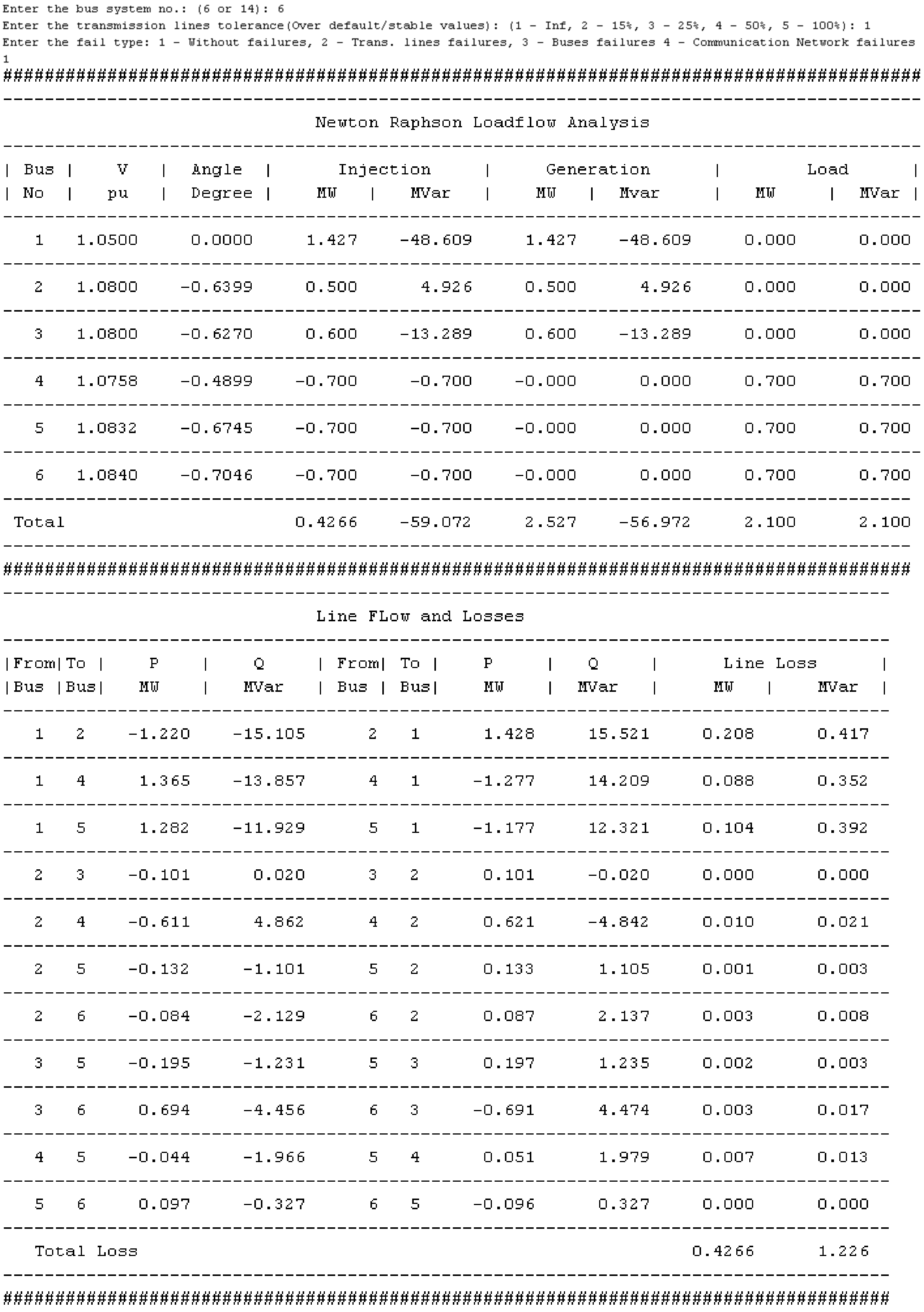
Note that in the case of a power link loss, the model reroutes the flows that existed over the failing link over the other available power links. It keeps track of the available components and maintains the balance between demand and supply, and abides the power lines capacity constraint either under normal operation or subject to disturbances.

Chapter 4 – Experiments

4.1 Simulation Results and Analysis

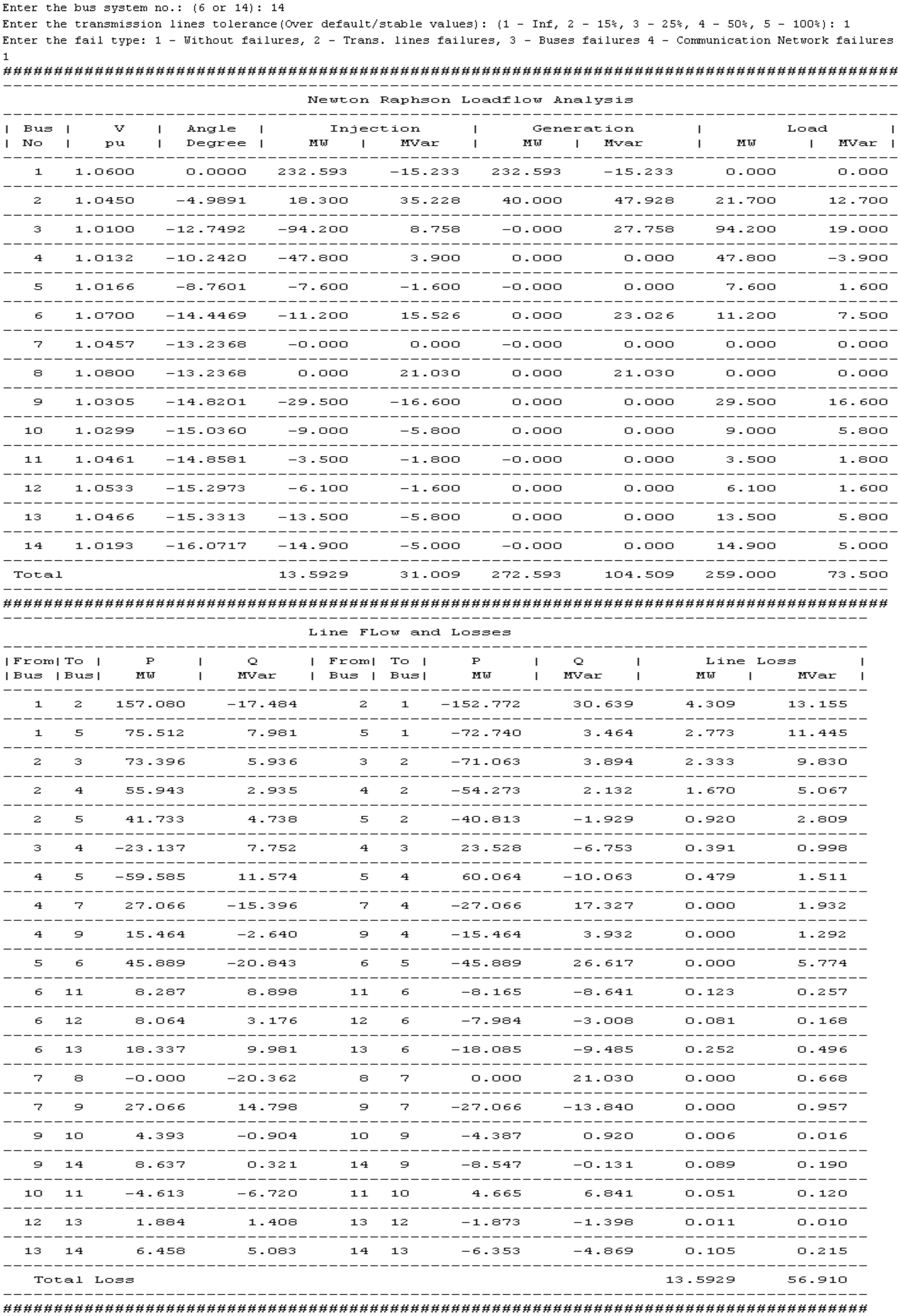
The simulations were carried out by the developed MATLAB software. The models were tested on IEEE 6-bus and IEEE 14-bus systems. The Power World Simulator was used to validate the results on the power network components. For the detailed characteristics of the systems used in the experiments, see Appendix I. We started by selecting one (or more) component(s) as the initial failure and then we ran the model for different test cases, with different transmission lines capacities and different initial component failure(s) to analyse the impacts of those failures. We differentiate power network failures and communication failures (Sections 4.1.1 and 4.1.2) to capture the interdependency of both networks and verify that a failure in one of them may cause failures in the other. Since the results of the simulations carried out have a high volume, in the following sections of this chapter we present only some of the tests in which the interdependency impacts of the power and communication networks are more noticeable. The remaining simulations were referred to Appendix II.

Figures 4.1.1 and 4.1.2 show the output of the software for the two systems used, without considering line capacities or failures in any of the networks. The software output provides information about the bus voltages and phase angle voltages, active and reactive power flows across the transmission lines, bus power injections, and generation and load values.



```
Enter the bus system no.: (6 or 14): 6
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 1
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
1
#########################################################################################
-----------------------------------------------------------------------------------------
                              Newton Raphson Loadflow Analysis
-----------------------------------------------------------------------------------------
| Bus |    V    |  Angle  |      Injection      |     Generation      |       Load      |
| No  |   pu    | Degree  |   MW   |    MVar    |    MW   |  Mvar     |   MW    |  MVar |
-----------------------------------------------------------------------------------------
   1   1.0500    0.0000    1.427    -48.609     1.427    -48.609     0.000      0.000
-----------------------------------------------------------------------------------------
   2   1.0800   -0.6399    0.500      4.926     0.500      4.926     0.000      0.000
-----------------------------------------------------------------------------------------
   3   1.0800   -0.6270    0.600    -13.289     0.600    -13.289     0.000      0.000
-----------------------------------------------------------------------------------------
   4   1.0758   -0.4899   -0.700     -0.700    -0.000      0.000     0.700      0.700
-----------------------------------------------------------------------------------------
   5   1.0832   -0.6745   -0.700     -0.700    -0.000      0.000     0.700      0.700
-----------------------------------------------------------------------------------------
   6   1.0840   -0.7046   -0.700     -0.700    -0.000      0.000     0.700      0.700
----------------------------------------------------------------------------------------
 Total                    0.4266    -59.072     2.527    -56.972     2.100      2.100
----------------------------------------------------------------------------------------
########################################################################################
--------------------------------------------------------------------------------------
                              Line FLow and Losses
--------------------------------------------------------------------------------------
|From|To |    P     |    Q     | From| To |    P     |   Q     |      Line Loss      |
|Bus |Bus|   MW     |   MVar   | Bus | Bus|   MW     |  MVar   |    MW    |    MVar  |
--------------------------------------------------------------------------------------
   1   2   -1.220    -15.105     2    1     1.428    15.521     0.208      0.417
--------------------------------------------------------------------------------------
   1   4    1.365    -13.857     4    1    -1.277    14.209     0.088      0.352
--------------------------------------------------------------------------------------
   1   5    1.282    -11.929     5    1    -1.177    12.321     0.104      0.392
--------------------------------------------------------------------------------------
   2   3   -0.101      0.020     3    2     0.101    -0.020     0.000      0.000
--------------------------------------------------------------------------------------
   2   4   -0.611      4.862     4    2     0.621    -4.842     0.010      0.021
--------------------------------------------------------------------------------------
   2   5   -0.132     -1.101     5    2     0.133     1.105     0.001      0.003
--------------------------------------------------------------------------------------
   2   6   -0.084     -2.129     6    2     0.087     2.137     0.003      0.008
--------------------------------------------------------------------------------------
   3   5   -0.195     -1.231     5    3     0.197     1.235     0.002      0.003
--------------------------------------------------------------------------------------
   3   6    0.694     -4.456     6    3    -0.691     4.474     0.003      0.017
--------------------------------------------------------------------------------------
   4   5   -0.044     -1.966     5    4     0.051     1.979     0.007      0.013
--------------------------------------------------------------------------------------
   5   6    0.097     -0.327     6    5    -0.096     0.327     0.000      0.000
--------------------------------------------------------------------------------------
   Total Loss                                                  0.4266     1.226
--------------------------------------------------------------------------------------
######################################################################################
```

Fig. 4.1.1 – Standard IEEE 6-bus system PF results



```
Enter the bus system no.: (6 or 14): 14
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 1
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
1
#########################################################################################
-----------------------------------------------------------------------------------------
                             Newton Raphson Loadflow Analysis
-----------------------------------------------------------------------------------------
| Bus |     V     |  Angle  |      Injection      |      Generation      |        Load        |
| No  |    pu     |  Degree |     MW   |   MVar   |     MW    |  Mvar    |     MW    |  MVar  |
-----------------------------------------------------------------------------------------
   1   1.0600     0.0000   232.593    -15.233   232.593    -15.233      0.000      0.000
-----------------------------------------------------------------------------------------
   2   1.0450    -4.9891    18.300     35.228    40.000     47.928     21.700     12.700
-----------------------------------------------------------------------------------------
   3   1.0100   -12.7492   -94.200      8.758    -0.000     27.758     94.200     19.000
-----------------------------------------------------------------------------------------
   4   1.0132   -10.2420   -47.800      3.900     0.000      0.000     47.800     -3.900
-----------------------------------------------------------------------------------------
   5   1.0166    -8.7601    -7.600     -1.600    -0.000      0.000      7.600      1.600
-----------------------------------------------------------------------------------------
   6   1.0700   -14.4469   -11.200     15.526     0.000     23.026     11.200      7.500
-----------------------------------------------------------------------------------------
   7   1.0457   -13.2368    -0.000      0.000    -0.000      0.000      0.000      0.000
-----------------------------------------------------------------------------------------
   8   1.0800   -13.2368     0.000     21.030     0.000     21.030      0.000      0.000
-----------------------------------------------------------------------------------------
   9   1.0305   -14.8201   -29.500    -16.600     0.000      0.000     29.500     16.600
-----------------------------------------------------------------------------------------
  10   1.0299   -15.0360    -9.000     -5.800     0.000      0.000      9.000      5.800
-----------------------------------------------------------------------------------------
  11   1.0461   -14.8581    -3.500     -1.800    -0.000      0.000      3.500      1.800
-----------------------------------------------------------------------------------------
  12   1.0533   -15.2973    -6.100     -1.600     0.000      0.000      6.100      1.600
-----------------------------------------------------------------------------------------
  13   1.0466   -15.3313   -13.500     -5.800     0.000      0.000     13.500      5.800
-----------------------------------------------------------------------------------------
  14   1.0193   -16.0717   -14.900     -5.000    -0.000      0.000     14.900      5.000
-----------------------------------------------------------------------------------------
 Total                     13.5929     31.009   272.593    104.509    259.000     73.500
-----------------------------------------------------------------------------------------
#########################################################################################
-----------------------------------------------------------------------------------------
                              Line FLow and Losses
-----------------------------------------------------------------------------------------
|From|To |     P     |     Q     | From| To |     P     |    Q     |      Line Loss       |
|Bus |Bus|    MW     |    MVar   | Bus | Bus|    MW     |   MVar   |     MW    |   MVar   |
-----------------------------------------------------------------------------------------
   1   2   157.080    -17.484      2    1   -152.772     30.639      4.309     13.155
-----------------------------------------------------------------------------------------
   1   5    75.512      7.981      5    1    -72.740      3.464      2.773     11.445
-----------------------------------------------------------------------------------------
   2   3    73.396      5.936      3    2    -71.063      3.894      2.333      9.830
-----------------------------------------------------------------------------------------
   2   4    55.943      2.935      4    2    -54.273      2.132      1.670      5.067
-----------------------------------------------------------------------------------------
   2   5    41.733      4.738      5    2    -40.813     -1.929      0.920      2.809
-----------------------------------------------------------------------------------------
   3   4   -23.137      7.752      4    3     23.528     -6.753      0.391      0.998
-----------------------------------------------------------------------------------------
   4   5   -59.585     11.574      5    4     60.064    -10.063      0.479      1.511
-----------------------------------------------------------------------------------------
   4   7    27.066    -15.396      7    4    -27.066     17.327      0.000      1.932
-----------------------------------------------------------------------------------------
   4   9    15.464     -2.640      9    4    -15.464      3.932      0.000      1.292
-----------------------------------------------------------------------------------------
   5   6    45.889    -20.843      6    5    -45.889     26.617      0.000      5.774
-----------------------------------------------------------------------------------------
   6  11     8.287      8.898     11    6     -8.165     -8.641      0.123      0.257
-----------------------------------------------------------------------------------------
   6  12     8.064      3.176     12    6     -7.984     -3.008      0.081      0.168
-----------------------------------------------------------------------------------------
   6  13    18.337      9.981     13    6    -18.085     -9.485      0.252      0.496
-----------------------------------------------------------------------------------------
   7   8    -0.000    -20.362      8    7      0.000     21.030      0.000      0.668
-----------------------------------------------------------------------------------------
   7   9    27.066     14.798      9    7    -27.066    -13.840      0.000      0.957
-----------------------------------------------------------------------------------------
   9  10     4.393     -0.904     10    9     -4.387      0.920      0.006      0.016
-----------------------------------------------------------------------------------------
   9  14     8.637      0.321     14    9     -8.547     -0.131      0.089      0.190
-----------------------------------------------------------------------------------------
  10  11    -4.613     -6.720     11   10      4.665      6.841      0.051      0.120
-----------------------------------------------------------------------------------------
  12  13     1.884      1.408     13   12     -1.873     -1.398      0.011      0.010
-----------------------------------------------------------------------------------------
  13  14     6.458      5.083     14   13     -6.353     -4.869      0.105      0.215
-----------------------------------------------------------------------------------------
   Total Loss                                                      13.5929     56.910
-----------------------------------------------------------------------------------------
#########################################################################################
```

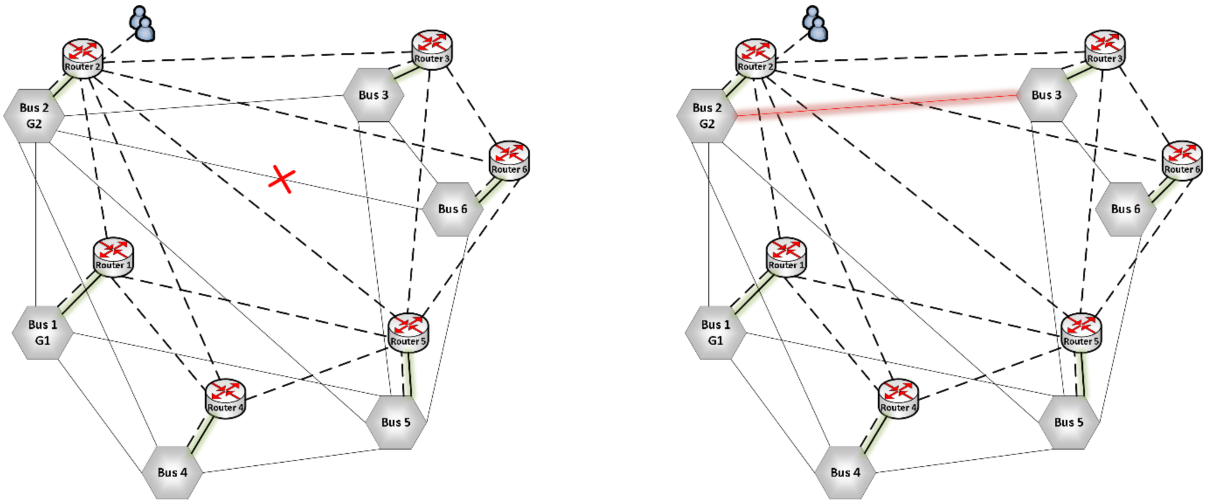
Fig. 4.1.2 – Standard IEEE 14-bus system PF results

4.1.1 Power Network Failures

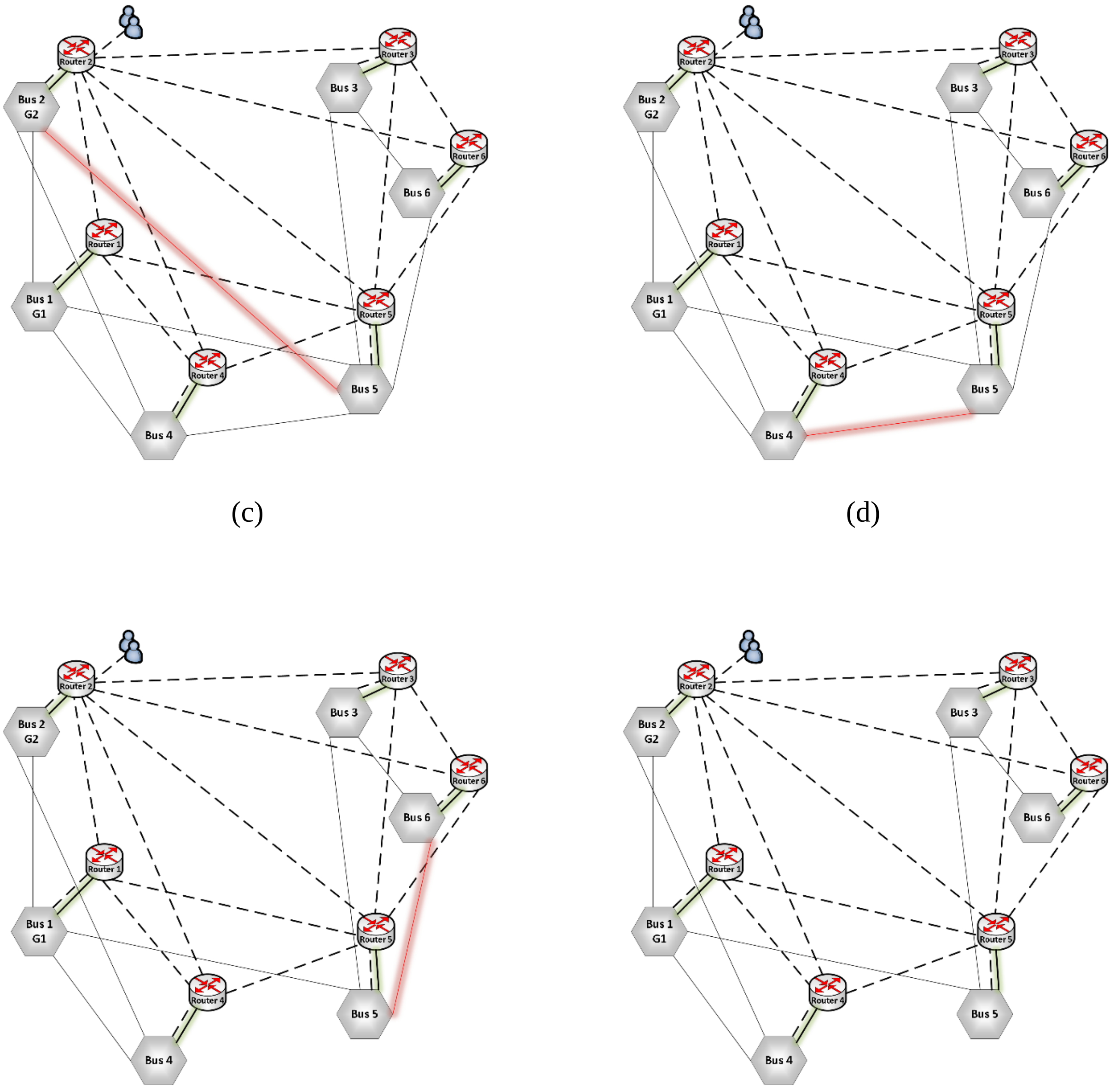
This section presents the impact of failures originating in components of the power network and will be divided into three subsections. Section 4.1.1.1 will present two examples of simulations in which the failure of a single transmission line led to a cascade of failures. In Section 4.1.1.2 the same type of analysis is done for a failure of another component of the power grid, in particular for the IEEE 14-bus system test case with a single bus as initial component failure. Lastly, in Section 4.1.1.3 the cascading failure analysis will be performed considering multiple initial failures of transmission lines.

4.1.1.1 Single Line Failures

Taking into account the fact that most of the recent blackouts were initiated by a failure of a single transmission line [10], this simulation approach was conducted. Fig. 4.1.1.1.1 shows an example of the cascading effects caused by the failure of a single line on the IEEE 6-bus system.



(a) (b)

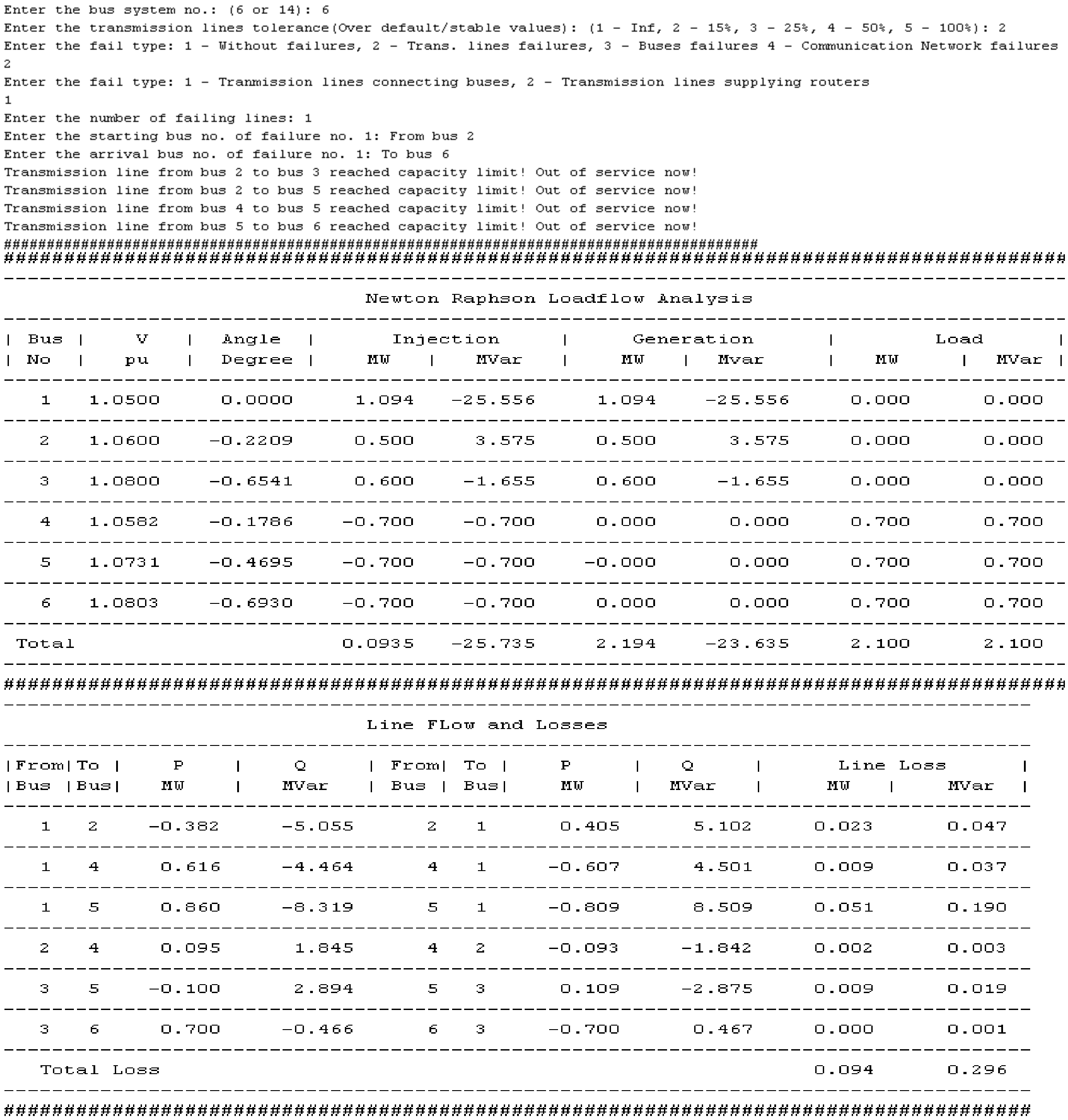


(c) (d)

(e) (f)

Fig. 4.1.1.1.1 – Example of a cascading failure demonstration caused by a single line failure on IEEE 6-bus system

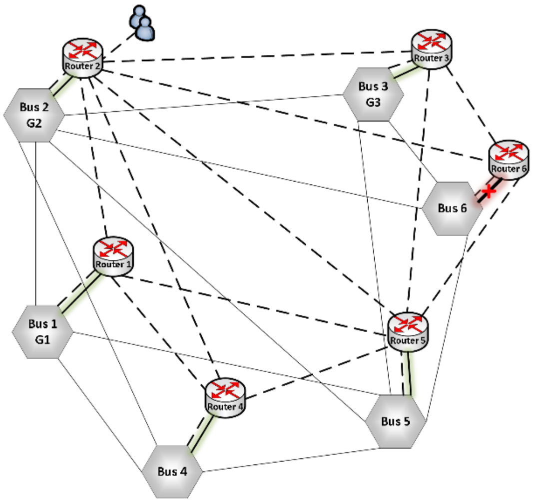
We took as an example the failure of the transmission line connecting bus 2 to bus 6. It should be noted that with this initial fault, for 15%, 25%, 50% and 100% tolerance of the line capacities, the results obtained regarding the component failures were the same, as can be seen on Table AII.1 in Appendix II. The initial fault is indicated using a red cross in Fig. 4.1.1.1.1(a). When the failure occurs, the system has to redistribute the power over the remaining lines. As a consequence, shown in Fig. 4.1.1.1.1(b) in shaded red, the transmission line from bus 2 to bus 3 was overloaded. Once a transmission line is overloaded, it becomes unavailable to prevent further damages. From the new flow redistribution, a new overload appeared. This time, the transmission line connecting bus 2 to bus 5 reached its capacity limits (Fig. 4.1.1.1.1 (c)). The redistribution process is repeated whenever any line reaches its capacity limit. Figures 4.1.1.1.1(d) and 4.1.1.1.1(e) show the subsequent overloads on transmission lines that connected bus 4 to bus 5 and bus 5 to bus 6, respectively. The surviving components after the cascade of failures are shown in Fig. 4.1.1.1.1(f). More detailed characteristics are presented in Fig. 4.1.1.1.2. The software output provides information about the failures subsequent to the initial failure.



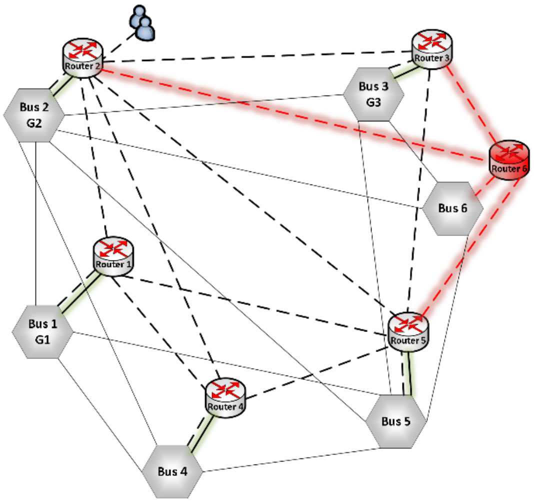
```
Enter the bus system no.: (6 or 14): 6
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 2
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
2
Enter the fail type: 1 - Tranmission lines connecting buses, 2 - Transmission lines supplying routers
1
Enter the number of failing lines: 1
Enter the starting bus no. of failure no. 1: From bus 2
Enter the arrival bus no. of failure no. 1: To bus 6
Transmission line from bus 2 to bus 3 reached capacity limit! Out of service now!
Transmission line from bus 2 to bus 5 reached capacity limit! Out of service now!
Transmission line from bus 4 to bus 5 reached capacity limit! Out of service now!
Transmission line from bus 5 to bus 6 reached capacity limit! Out of service now!
###################################################################################################################
########################################################################################
----------------------------------------------------------------------------------------
                              Newton Raphson Loadflow Analysis
----------------------------------------------------------------------------------------
| Bus |     V    |  Angle  |      Injection      |      Generation      |       Load        |
| No  |    pu    |  Degree |    MW    |   MVar    |    MW    |   Mvar    |    MW     |  MVar |
----------------------------------------------------------------------------------------
   1   1.0500     0.0000     1.094    -25.556     1.094    -25.556     0.000      0.000
----------------------------------------------------------------------------------------
   2   1.0600    -0.2209     0.500      3.575     0.500      3.575     0.000      0.000
----------------------------------------------------------------------------------------
   3   1.0800    -0.6541     0.600     -1.655     0.600     -1.655     0.000      0.000
----------------------------------------------------------------------------------------
   4   1.0582    -0.1786    -0.700     -0.700     0.000      0.000     0.700      0.700
----------------------------------------------------------------------------------------
   5   1.0731    -0.4695    -0.700     -0.700    -0.000      0.000     0.700      0.700
----------------------------------------------------------------------------------------
   6   1.0803    -0.6930    -0.700     -0.700     0.000      0.000     0.700      0.700
----------------------------------------------------------------------------------------
 Total                      0.0935    -25.735     2.194    -23.635     2.100      2.100
----------------------------------------------------------------------------------------
########################################################################################
-------------------------------------------------------------------------------------
                              Line FLow and Losses
-------------------------------------------------------------------------------------
|From|To |     P     |     Q     | From| To |     P     |    Q     |      Line Loss     |
|Bus |Bus|    MW     |    MVar   | Bus | Bus|    MW     |   MVar   |    MW    |   MVar  |
-------------------------------------------------------------------------------------
   1   2    -0.382     -5.055       2    1      0.405      5.102     0.023      0.047
-------------------------------------------------------------------------------------
   1   4     0.616     -4.464       4    1     -0.607      4.501     0.009      0.037
-------------------------------------------------------------------------------------
   1   5     0.860     -8.319       5    1     -0.809      8.509     0.051      0.190
-------------------------------------------------------------------------------------
   2   4     0.095      1.845       4    2     -0.093     -1.842     0.002      0.003
-------------------------------------------------------------------------------------
   3   5    -0.100      2.894       5    3      0.109     -2.875     0.009      0.019
-------------------------------------------------------------------------------------
   3   6     0.700     -0.466       6    3     -0.700      0.467     0.000      0.001
-------------------------------------------------------------------------------------
   Total Loss                                                        0.094      0.296
-------------------------------------------------------------------------------------
#####################################################################################
```

Fig. 4.1.1.1.2 – Output of the developed software for the example in Fig. 4.1.1.1.1

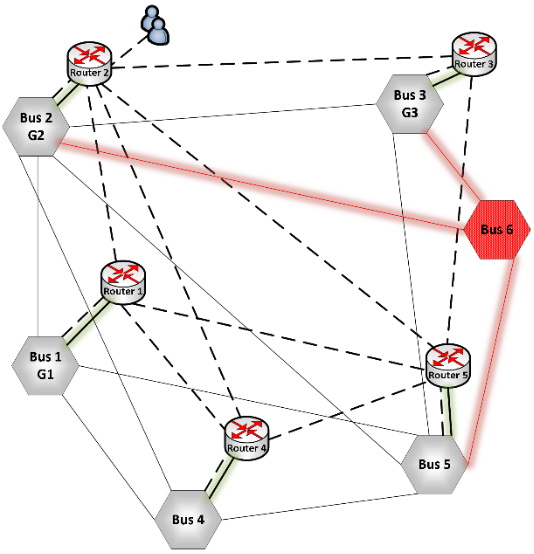
The previous example only addresses power network faults to understand how this part of the system behaves. To clearly visualize the interdependency of power and communication networks, the following example (depicted in Fig. 4.1.1.1.3) illustrates the effects of the failure of a single transmission line which supplied power to a router. This simulation was performed on IEEE 6-bus system and the results obtained regarding component failures were the same for all the modeled capacities to this system.


Router 2
Router 3
Bus 3
G3
Bus 2
G2
Router 6
Bus 6
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

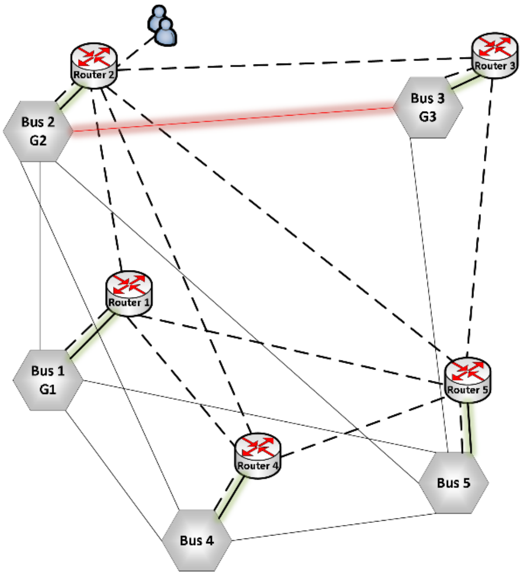
(a)


Router 2
Router 3
Bus 3
G3
Bus 2
G2
Router 6
Bus 6
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

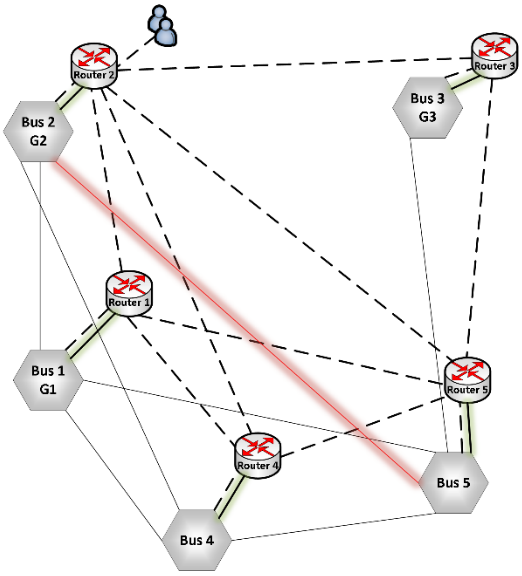
(b)


Router 2
Router 3
Bus 3
G3
Bus 2
G2
Bus 6
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

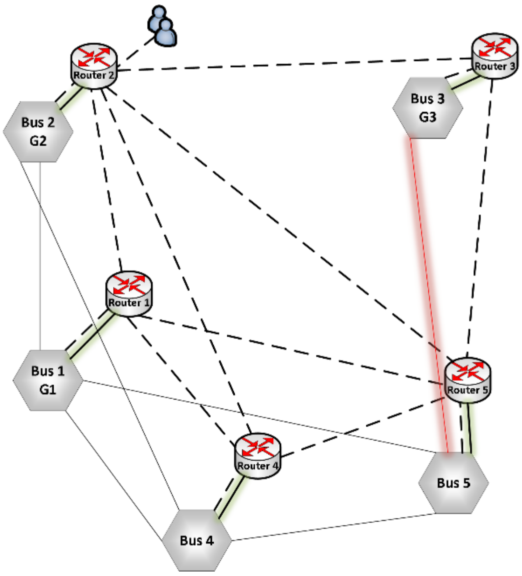
(c)


Router 2
Router 3
Bus 3
G3
Bus 2
G2
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

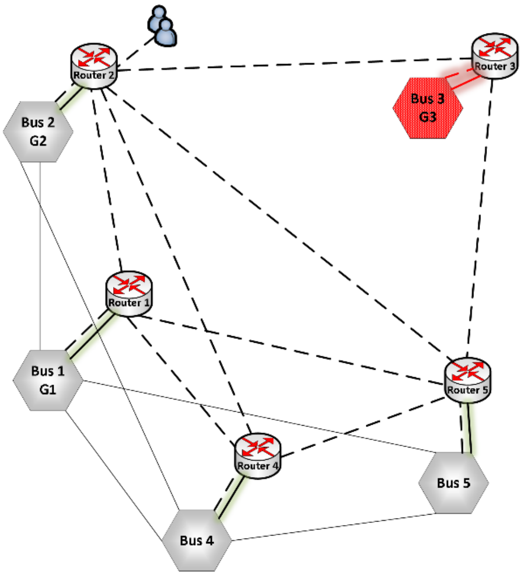
(d)


Router 2
Router 3
Bus 2
G2
Bus 3
G3
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

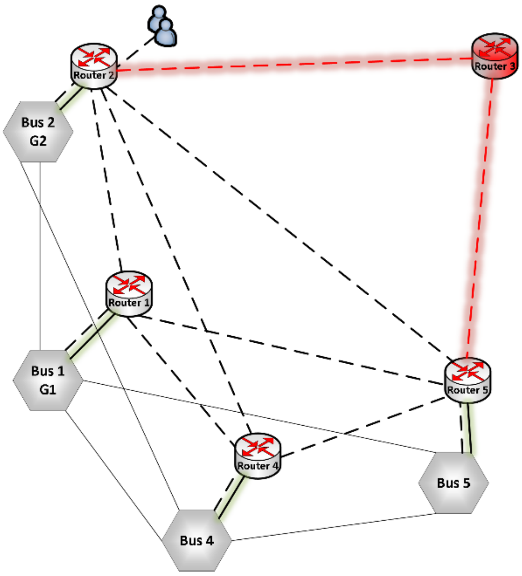
(e)


Router 2
Router 3
Bus 2
G2
Bus 3
G3
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

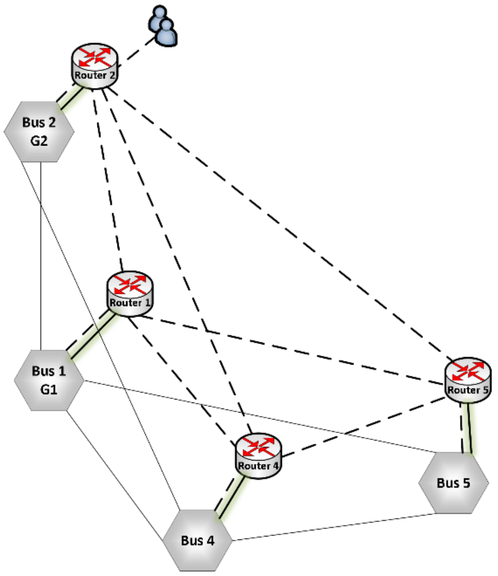
(f)


Router 2
Router 3
Bus 2
G2
Bus 3
G3
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

(g)


Router 2
Router 3
Bus 2
G2
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

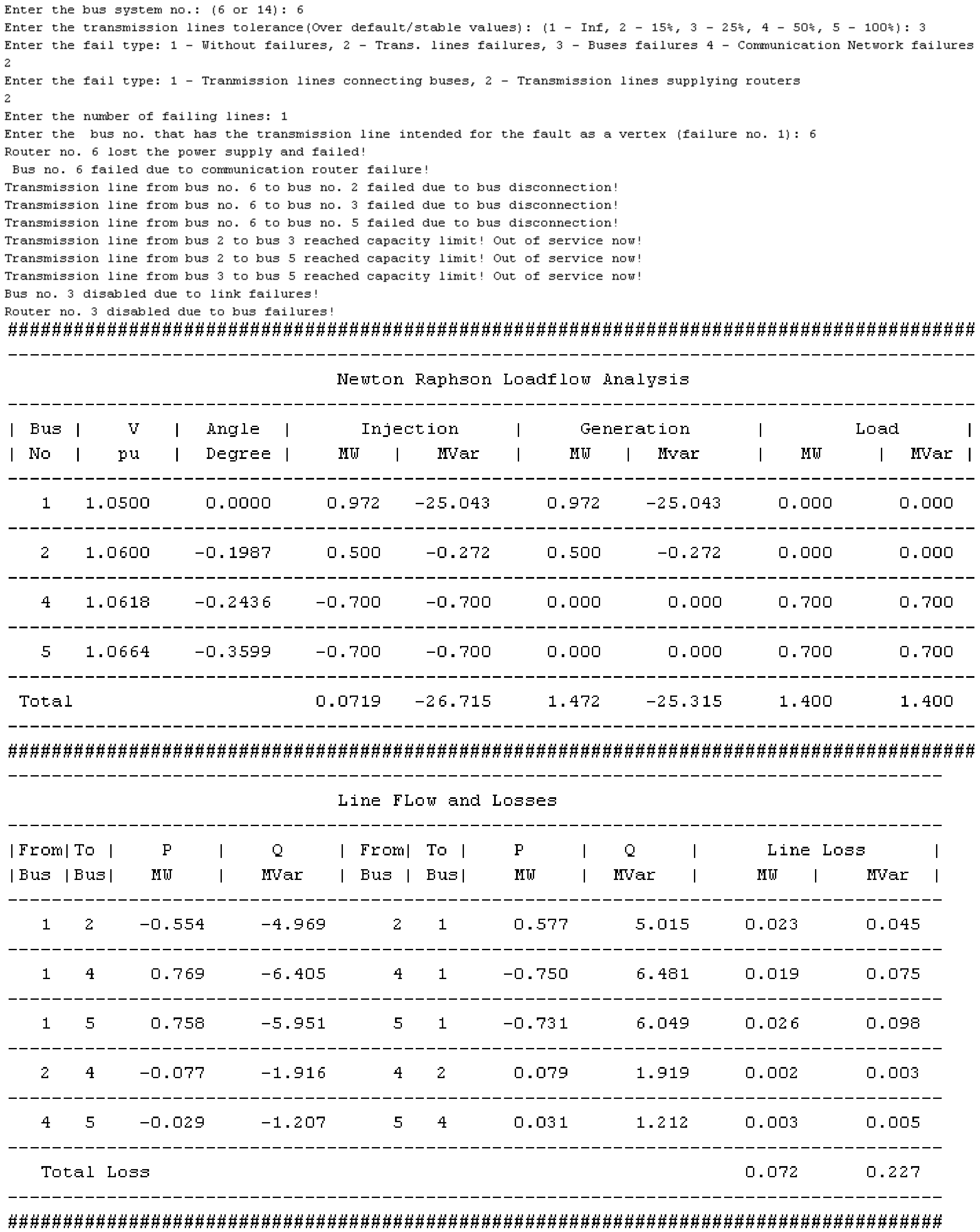
(h)



(i)

Fig. 4.1.1.1.3 – Cascading failure schema caused by a single line failure on IEEE 6-bus system

Here, the transmission line supplying router number 6 fails (Fig. 4.1.1.1.3(a)). Consequently, this router loses the power to operate and is disconnected, losing the communications with other elements of the network (Fig. 4.1.1.1.3(b)). Since the busbar number 6 depended on the communications provided by the router 6 to function properly, this bus also fails (Fig. 4.1.1.1.3(c)). After these failures, with the redistribution of power flows, three transmission lines become overloaded (Figures 4.1.1.1.3(d), 4.1.1.1.3(e) and 4.1.1.1.3(f)). From this cascade of overloads, the lack of transmission lines connected to the generator in bus 3 led to its disconnection (Fig. 4.1.1.1.3(g)). Due to insufficient power supply, router number 3 also fails (Fig. 4.1.1.1.3(h)). The final system state is shown in Fig. 4.1.1.1.3(i).



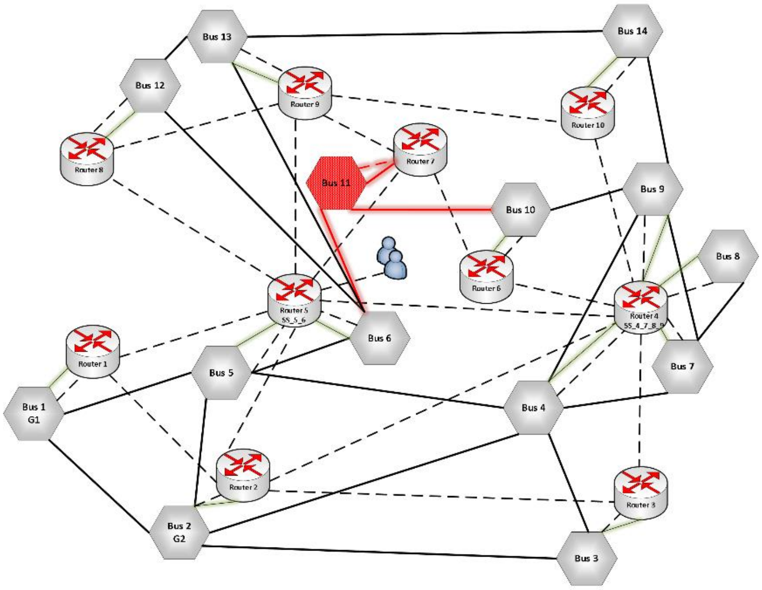
```
Enter the bus system no.: (6 or 14): 6
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 3
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
2
Enter the fail type: 1 - Tranmission lines connecting buses, 2 - Transmission lines supplying routers
2
Enter the number of failing lines: 1
Enter the  bus no. that has the transmission line intended for the fault as a vertex (failure no. 1): 6
Router no. 6 lost the power supply and failed!
 Bus no. 6 failed due to communication router failure!
Transmission line from bus no. 6 to bus no. 2 failed due to bus disconnection!
Transmission line from bus no. 6 to bus no. 3 failed due to bus disconnection!
Transmission line from bus no. 6 to bus no. 5 failed due to bus disconnection!
Transmission line from bus 2 to bus 3 reached capacity limit! Out of service now!
Transmission line from bus 2 to bus 5 reached capacity limit! Out of service now!
Transmission line from bus 3 to bus 5 reached capacity limit! Out of service now!
Bus no. 3 disabled due to link failures!
Router no. 3 disabled due to bus failures!
########################################################################################
----------------------------------------------------------------------------------------
                              Newton Raphson Loadflow Analysis
----------------------------------------------------------------------------------------
| Bus |    V    |  Angle  |      Injection      |      Generation       |        Load      |
| No  |    pu   |  Degree |    MW    |   MVar   |     MW   |  Mvar      |    MW      |  MVar |
----------------------------------------------------------------------------------------
   1   1.0500     0.0000     0.972   -25.043     0.972    -25.043     0.000      0.000
----------------------------------------------------------------------------------------
   2   1.0600    -0.1987     0.500    -0.272     0.500     -0.272     0.000      0.000
----------------------------------------------------------------------------------------
   4   1.0618    -0.2436    -0.700    -0.700     0.000      0.000     0.700      0.700
----------------------------------------------------------------------------------------
   5   1.0664    -0.3599    -0.700    -0.700     0.000      0.000     0.700      0.700
----------------------------------------------------------------------------------------
 Total                      0.0719   -26.715     1.472    -25.315     1.400      1.400
----------------------------------------------------------------------------------------
########################################################################################
-------------------------------------------------------------------------------------
                              Line FLow and Losses
-------------------------------------------------------------------------------------
|From|To |    P     |    Q     | From| To |    P     |   Q      |     Line Loss      |
|Bus |Bus|   MW     |   MVar   | Bus | Bus|   MW     |  MVar    |    MW   |    MVar  |
-------------------------------------------------------------------------------------
   1   2   -0.554     -4.969      2    1      0.577      5.015     0.023      0.045
-------------------------------------------------------------------------------------
   1   4    0.769     -6.405      4    1     -0.750      6.481     0.019      0.075
-------------------------------------------------------------------------------------
   1   5    0.758     -5.951      5    1     -0.731      6.049     0.026      0.098
-------------------------------------------------------------------------------------
   2   4   -0.077     -1.916      4    2      0.079      1.919     0.002      0.003
-------------------------------------------------------------------------------------
   4   5   -0.029     -1.207      5    4      0.031      1.212     0.003      0.005
-------------------------------------------------------------------------------------
   Total Loss                                                      0.072      0.227
-------------------------------------------------------------------------------------
#####################################################################################
```

Fig. 4.1.1.1.4 – Output of the developed software for the example in Fig. 4.1.1.1.3

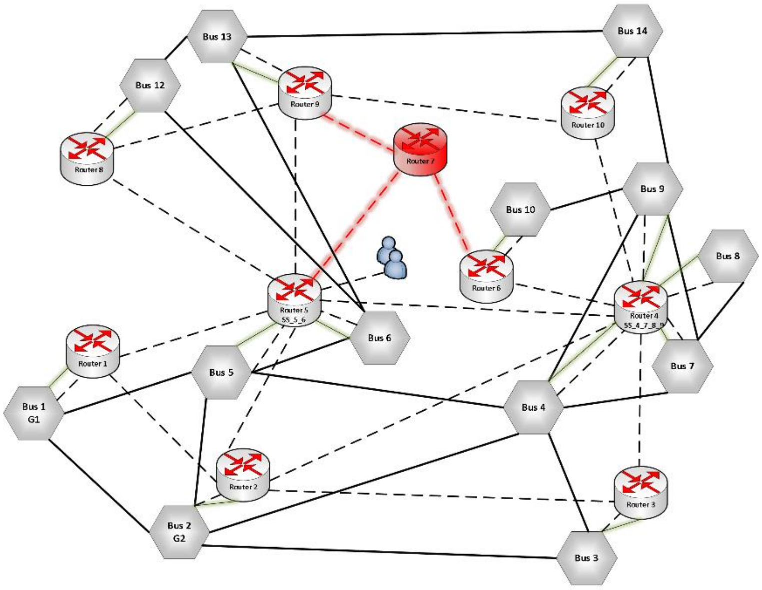
4.1.1.2 Bus Failures

As with transmission lines, bus faults may also occur for several reasons. For more details on bus failures, see [35].

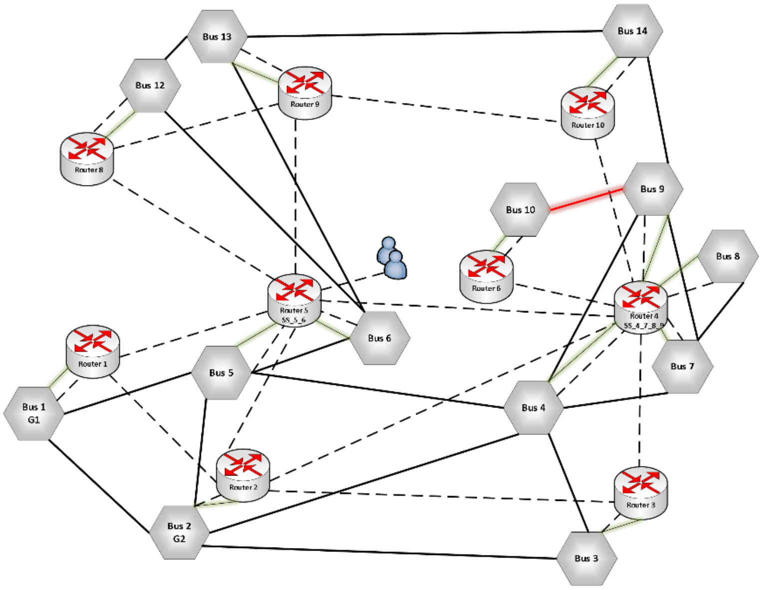
In this section, we selected bus 11 as the initial failing bus in the IEEE 14-bus system. The resulting cascading failures events are shown in Fig. 4.1.1.2.1. As in the previous example (Fig. 4.1.1.1.3), we chose a 15% tolerance for the line capacities of the system.



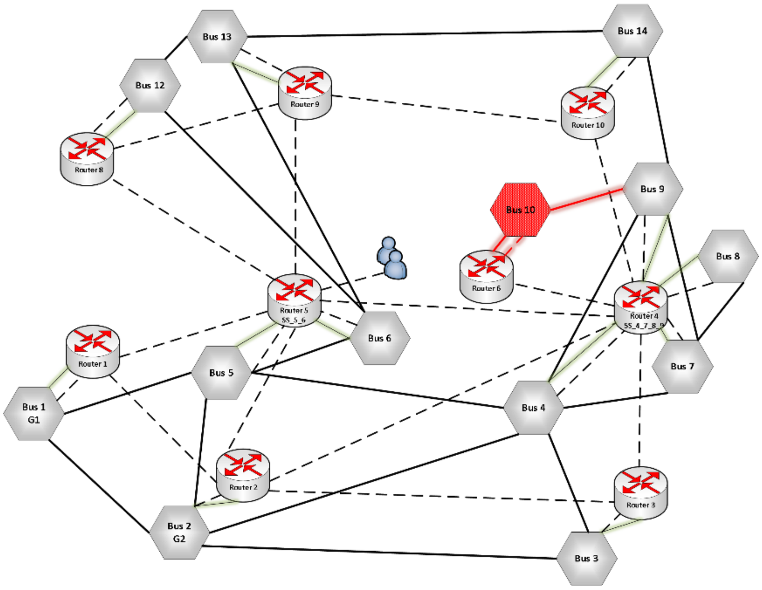
(a)


Bus 13
Bus 14
Bus 12
Router 9
Router 10
Router 8
Router 7
Bus 10
Bus 9
Bus 8
Router 6
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

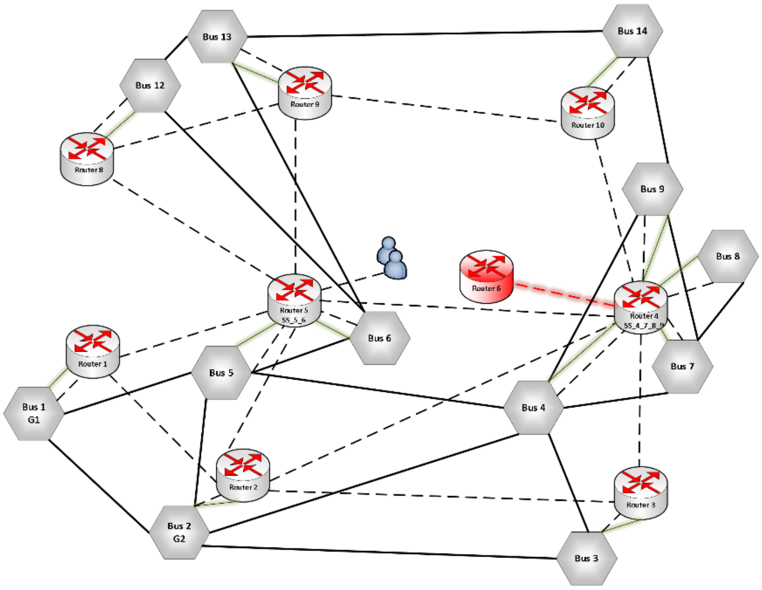
(b)


Bus 13
Bus 14
Bus 12
Router 9
Router 10
Router 8
Bus 10
Bus 9
Bus 8
Router 6
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

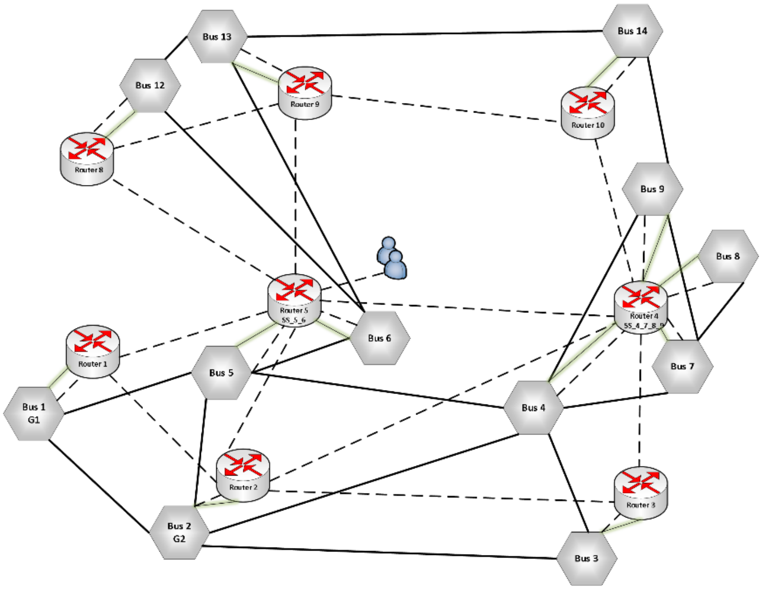
(c)


Bus 13
Bus 14
Bus 12
Router 9
Router 10
Router 8
Bus 9
Bus 10
Router 6
Bus 8
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

(d)


Bus 13
Bus 14
Bus 12
Router 9
Router 10
Router 8
Bus 9
Router 6
Bus 8
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

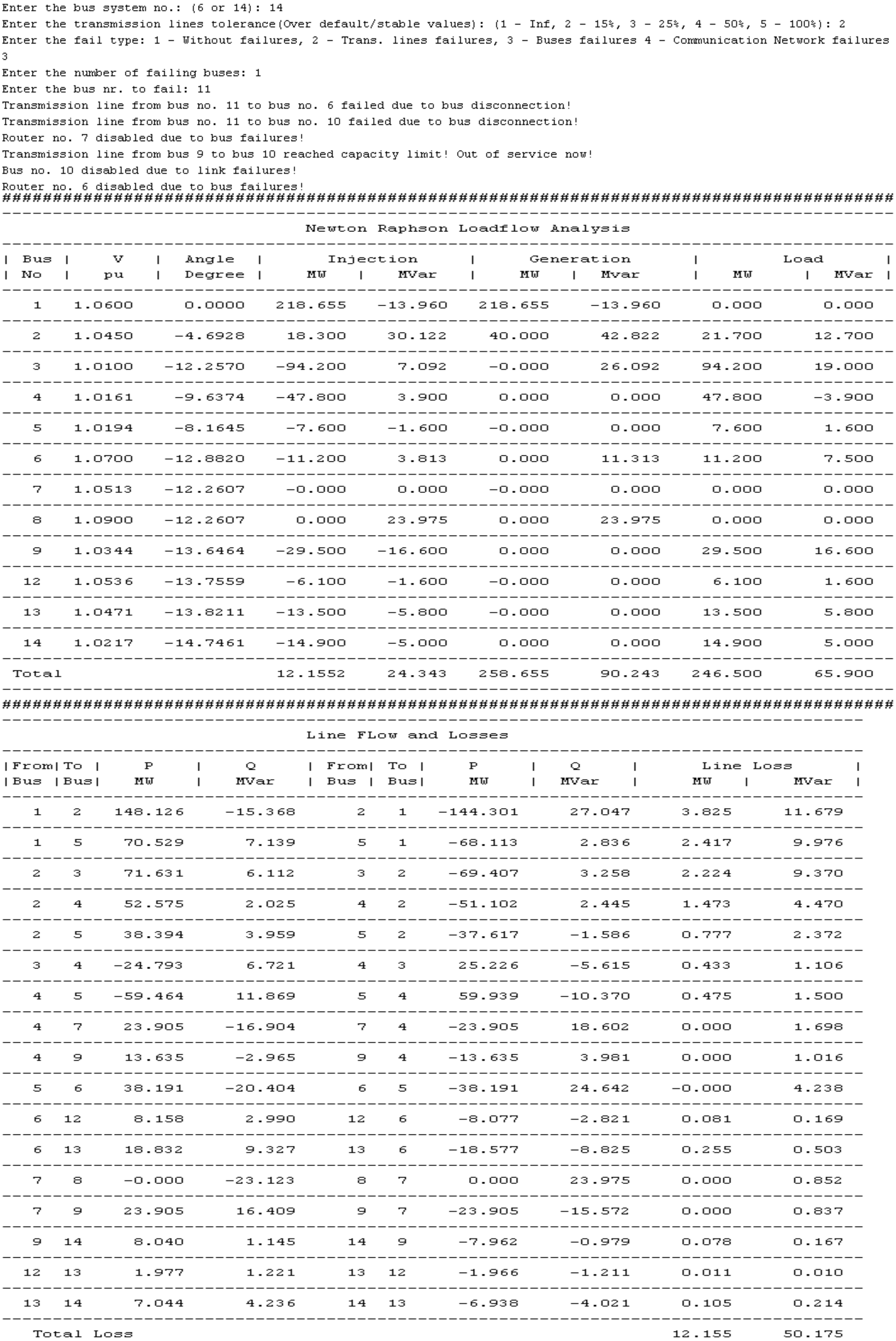
(e)



(f)

Fig. 4.1.1.2.1 - Schema of a cascading failure caused by a bus failure

After the initial failure (Fig. 4.1.1.2.1(a)), router number 7 loses its power source that was supplied by the bus 11 and consequently it becomes unavailable (Fig. 4.1.1.2.1(b)). Then, the power flows are redistributed which results in the overload of transmission line from bus 9 to bus 10 (Fig. 4.1.1.2.1(c)). Since this transmission line was the only one that connected bus number 10 to the power network, this bus also fails (Fig. 4.1.1.2.1(d)). Finally, as with the router number 7, due to the lack of power supply, the router number 6 also fails (Fig. 4.1.1.2.1(e)). The system after the cascade is depicted in Fig. 4.1.1.2.1(f). The detailed characteristics of this cascading event are shown in Fig. 4.1.1.2.2.

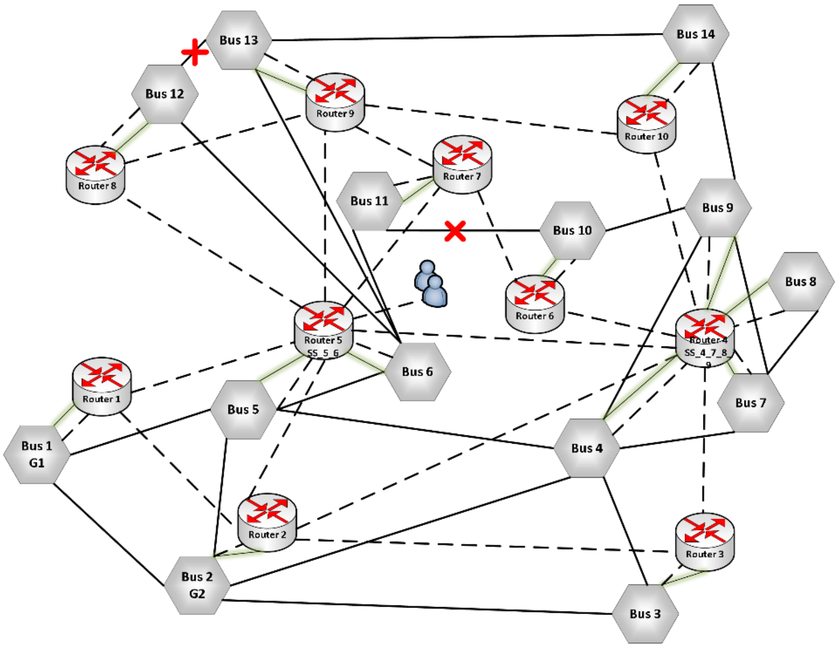


```
Enter the bus system no.: (6 or 14): 14
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 2
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
3
Enter the number of failing buses: 1
Enter the bus nr. to fail: 11
Transmission line from bus no. 11 to bus no. 6 failed due to bus disconnection!
Transmission line from bus no. 11 to bus no. 10 failed due to bus disconnection!
Router no. 7 disabled due to bus failures!
Transmission line from bus 9 to bus 10 reached capacity limit! Out of service now!
Bus no. 10 disabled due to link failures!
Router no. 6 disabled due to bus failures!
###############################################################################################
-----------------------------------------------------------------------------------------------
                           Newton Raphson Loadflow Analysis
-----------------------------------------------------------------------------------------------
| Bus |    V    |  Angle  |      Injection      |     Generation      |          Load         |
| No  |   pu    | Degree  |    MW    |   MVar   |    MW    |   Mvar   |    MW       |   MVar  |
-----------------------------------------------------------------------------------------------
   1   1.0600     0.0000   218.655   -13.960   218.655    -13.960     0.000       0.000
-----------------------------------------------------------------------------------------------
   2   1.0450    -4.6928    18.300    30.122    40.000     42.822    21.700      12.700
-----------------------------------------------------------------------------------------------
   3   1.0100   -12.2570   -94.200     7.092    -0.000     26.092    94.200      19.000
-----------------------------------------------------------------------------------------------
   4   1.0161    -9.6374   -47.800     3.900     0.000      0.000    47.800      -3.900
-----------------------------------------------------------------------------------------------
   5   1.0194    -8.1645    -7.600    -1.600    -0.000      0.000     7.600       1.600
-----------------------------------------------------------------------------------------------
   6   1.0700   -12.8820   -11.200     3.813     0.000     11.313    11.200       7.500
-----------------------------------------------------------------------------------------------
   7   1.0513   -12.2607    -0.000     0.000    -0.000      0.000     0.000       0.000
-----------------------------------------------------------------------------------------------
   8   1.0900   -12.2607     0.000    23.975     0.000     23.975     0.000       0.000
-----------------------------------------------------------------------------------------------
   9   1.0344   -13.6464   -29.500   -16.600     0.000      0.000    29.500      16.600
-----------------------------------------------------------------------------------------------
  12   1.0536   -13.7559    -6.100    -1.600    -0.000      0.000     6.100       1.600
-----------------------------------------------------------------------------------------------
  13   1.0471   -13.8211   -13.500    -5.800    -0.000      0.000    13.500       5.800
-----------------------------------------------------------------------------------------------
  14   1.0217   -14.7461   -14.900    -5.000     0.000      0.000    14.900       5.000
-----------------------------------------------------------------------------------------------
 Total                     12.1552    24.343   258.655     90.243   246.500      65.900
-----------------------------------------------------------------------------------------------
###############################################################################################
--------------------------------------------------------------------------------------------
                           Line FLow and Losses
--------------------------------------------------------------------------------------------
|From|To |    P      |    Q      | From| To |    P      |   Q      |      Line Loss        |
|Bus |Bus|   MW      |   MVar    | Bus | Bus|   MW      |  MVar    |    MW    |    MVar    |
--------------------------------------------------------------------------------------------
   1   2   148.126    -15.368       2    1   -144.301     27.047     3.825      11.679
--------------------------------------------------------------------------------------------
   1   5    70.529      7.139       5    1    -68.113      2.836     2.417       9.976
--------------------------------------------------------------------------------------------
   2   3    71.631      6.112       3    2    -69.407      3.258     2.224       9.370
--------------------------------------------------------------------------------------------
   2   4    52.575      2.025       4    2    -51.102      2.445     1.473       4.470
--------------------------------------------------------------------------------------------
   2   5    38.394      3.959       5    2    -37.617     -1.586     0.777       2.372
--------------------------------------------------------------------------------------------
   3   4   -24.793      6.721       4    3     25.226     -5.615     0.433       1.106
--------------------------------------------------------------------------------------------
   4   5   -59.464     11.869       5    4     59.939    -10.370     0.475       1.500
--------------------------------------------------------------------------------------------
   4   7    23.905    -16.904       7    4    -23.905     18.602     0.000       1.698
--------------------------------------------------------------------------------------------
   4   9    13.635     -2.965       9    4    -13.635      3.981     0.000       1.016
--------------------------------------------------------------------------------------------
   5   6    38.191    -20.404       6    5    -38.191     24.642    -0.000       4.238
--------------------------------------------------------------------------------------------
   6  12     8.158      2.990      12    6     -8.077     -2.821     0.081       0.169
--------------------------------------------------------------------------------------------
   6  13    18.832      9.327      13    6    -18.577     -8.825     0.255       0.503
--------------------------------------------------------------------------------------------
   7   8    -0.000    -23.123       8    7      0.000     23.975     0.000       0.852
--------------------------------------------------------------------------------------------
   7   9    23.905     16.409       9    7    -23.905    -15.572     0.000       0.837
--------------------------------------------------------------------------------------------
   9  14     8.040      1.145      14    9     -7.962     -0.979     0.078       0.167
--------------------------------------------------------------------------------------------
  12  13     1.977      1.221      13   12     -1.966     -1.211     0.011       0.010
--------------------------------------------------------------------------------------------
  13  14     7.044      4.236      14   13     -6.938     -4.021     0.105       0.214
--------------------------------------------------------------------------------------------
   Total Loss                                                        12.155      50.175
```

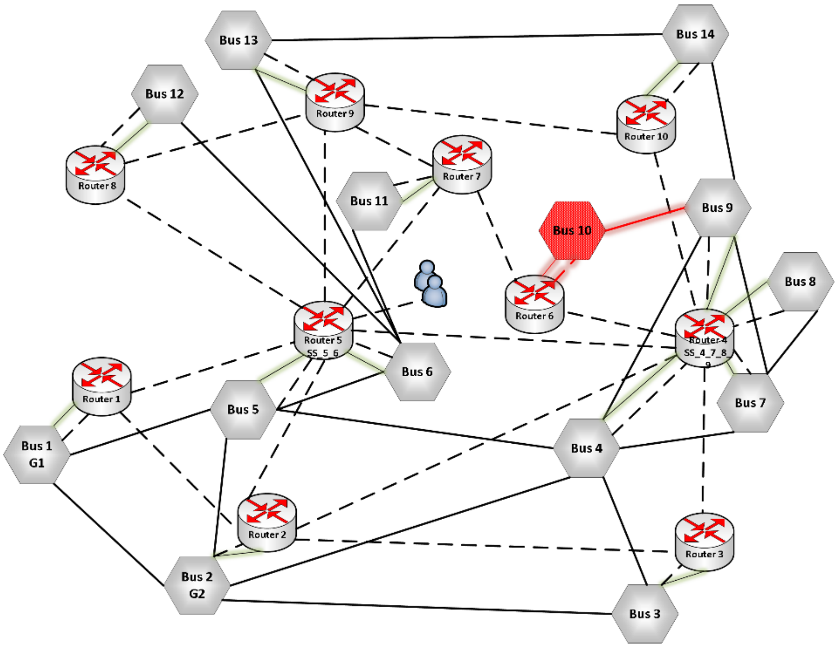
Fig. 4.1.1.2.2 - Output of the developed software for the example in Fig. 4.1.1.2.1

4.1.1.3 Multiline Failures

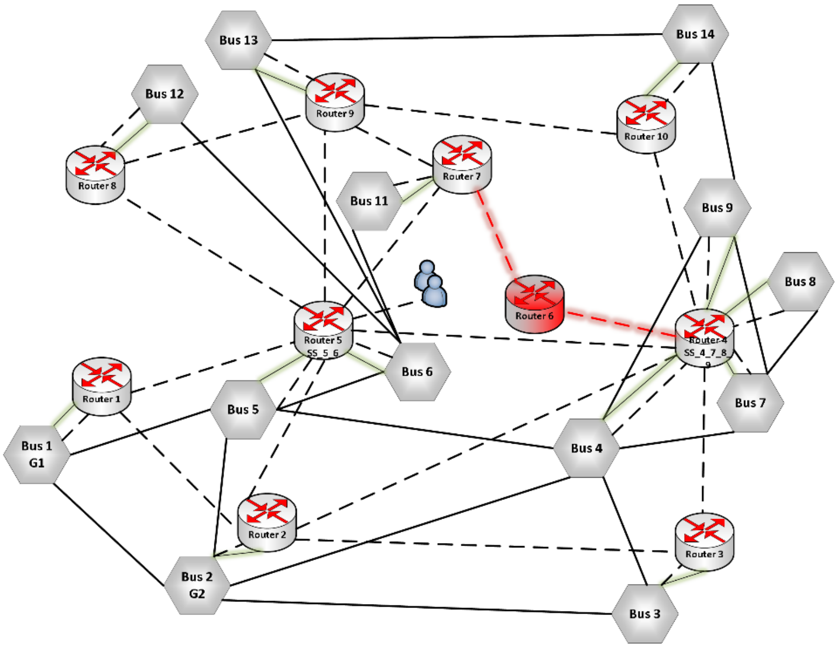
These type of failures are common in targeted attacks, either physical or cyber attacks. An example of a cascading failure on IEEE 14-bus system in which two power links were selected to fail is depicted in Fig. 4.1.1.3.1.



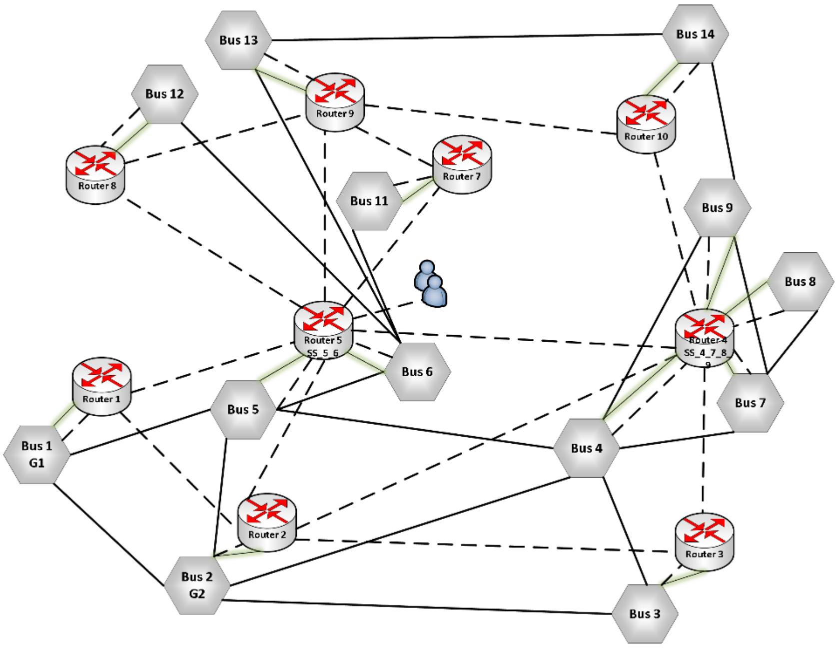
(a)


Bus 13
Bus 14
Bus 12
Router 9
Router 10
Router 8
Router 7
Bus 11
Bus 10
Bus 9
Bus 8
Router 6
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

(b)


Bus 13
Bus 14
Bus 12
Router 9
Router 10
Router 8
Router 7
Bus 11
Bus 9
Bus 8
Router 6
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

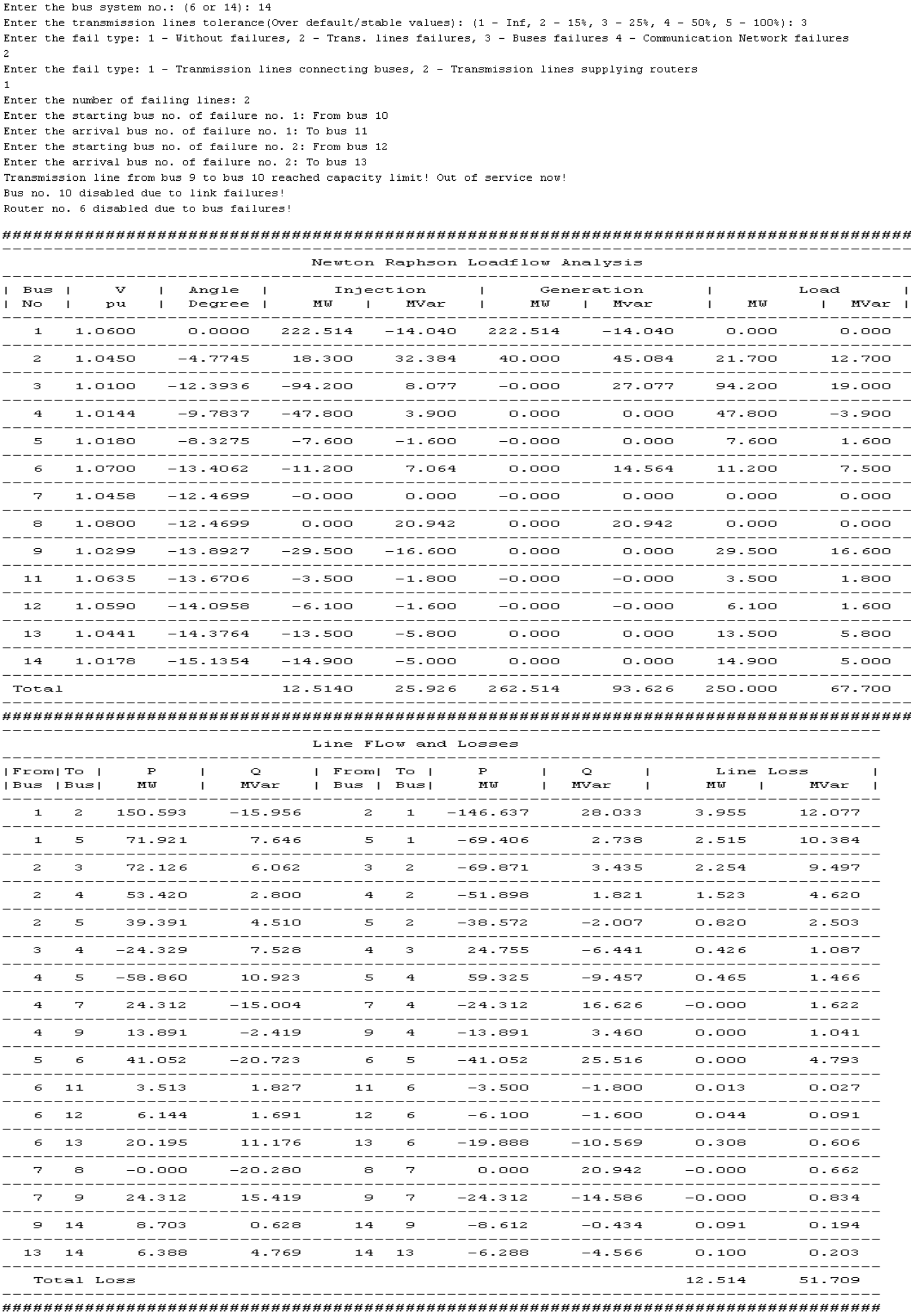
(c)



(d)

Fig. 4.1.1.3.1 – Schema of a cascading failure caused by a multiline failure

An initial fault affecting two transmission lines (out of the twenty four available) was considered. As in the examples in Section 4.1.1.1, the faults are indicated using a red cross in Fig. 4.1.1.3.1(a). The chosen links were the transmission lines from bus no.10 to bus no.11 and from bus no.12 to bus no.13. According to the model developed and described in the previous chapter, with a 25% line capacities tolerance, these initial disconnections led to the overload of the transmission line connecting bus no.9 to bus no.10. Such overload forced a reroute of the power flow that caused this transmission line to go out of service. Hence, due to the lack of active transmission lines connected to bus no.10, this bus was also disconnected from the system as can be seen in Fig. 4.1.1.3.1(b). With the loss of power supply in this node, router no.6 stopped receiving power and lost the ability to communicate with other routers and with the control center as shown in Fig. 4.1.1.3.1(c). The system schema after the cascade conclusion is depicted in Fig. 4.1.1.3.1(d). For detailed characteristics, see Fig. 4.1.1.3.2.



```
Enter the bus system no.: (6 or 14): 14
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 3
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
2
Enter the fail type: 1 - Tranmission lines connecting buses, 2 - Transmission lines supplying routers
1
Enter the number of failing lines: 2
Enter the starting bus no. of failure no. 1: From bus 10
Enter the arrival bus no. of failure no. 1: To bus 11
Enter the starting bus no. of failure no. 2: From bus 12
Enter the arrival bus no. of failure no. 2: To bus 13
Transmission line from bus 9 to bus 10 reached capacity limit! Out of service now!
Bus no. 10 disabled due to link failures!
Router no. 6 disabled due to bus failures!

##########################################################################################
------------------------------------------------------------------------------------------
                              Newton Raphson Loadflow Analysis
------------------------------------------------------------------------------------------
| Bus |     V    |  Angle  |      Injection       |      Generation       |        Load        |
| No  |    pu    |  Degree |    MW    |   MVar    |     MW    |  Mvar     |    MW    |  MVar   |
------------------------------------------------------------------------------------------
   1    1.0600     0.0000    222.514   -14.040    222.514    -14.040      0.000      0.000
------------------------------------------------------------------------------------------
   2    1.0450    -4.7745     18.300    32.384     40.000     45.084     21.700     12.700
------------------------------------------------------------------------------------------
   3    1.0100   -12.3936    -94.200     8.077     -0.000     27.077     94.200     19.000
------------------------------------------------------------------------------------------
   4    1.0144    -9.7837    -47.800     3.900      0.000      0.000     47.800     -3.900
------------------------------------------------------------------------------------------
   5    1.0180    -8.3275     -7.600    -1.600     -0.000      0.000      7.600      1.600
------------------------------------------------------------------------------------------
   6    1.0700   -13.4062    -11.200     7.064      0.000     14.564     11.200      7.500
------------------------------------------------------------------------------------------
   7    1.0458   -12.4699     -0.000     0.000     -0.000      0.000      0.000      0.000
------------------------------------------------------------------------------------------
   8    1.0800   -12.4699      0.000    20.942      0.000     20.942      0.000      0.000
------------------------------------------------------------------------------------------
   9    1.0299   -13.8927    -29.500   -16.600      0.000      0.000     29.500     16.600
------------------------------------------------------------------------------------------
  11    1.0635   -13.6706     -3.500    -1.800     -0.000     -0.000      3.500      1.800
------------------------------------------------------------------------------------------
  12    1.0590   -14.0958     -6.100    -1.600     -0.000     -0.000      6.100      1.600
------------------------------------------------------------------------------------------
  13    1.0441   -14.3764    -13.500    -5.800      0.000      0.000     13.500      5.800
------------------------------------------------------------------------------------------
  14    1.0178   -15.1354    -14.900    -5.000      0.000      0.000     14.900      5.000
------------------------------------------------------------------------------------------
 Total                       12.5140    25.926    262.514     93.626    250.000     67.700
------------------------------------------------------------------------------------------
##########################################################################################
---------------------------------------------------------------------------------------
                              Line FLow and Losses
---------------------------------------------------------------------------------------
|From|To |     P      |     Q      | From| To |     P      |     Q      |      Line Loss       |
|Bus |Bus|    MW      |    MVar    | Bus | Bus|    MW      |   MVar     |    MW    |   MVar    |
---------------------------------------------------------------------------------------
   1   2    150.593     -15.956       2    1    -146.637     28.033      3.955     12.077
---------------------------------------------------------------------------------------
   1   5     71.921       7.646       5    1     -69.406      2.738      2.515     10.384
---------------------------------------------------------------------------------------
   2   3     72.126       6.062       3    2     -69.871      3.435      2.254      9.497
---------------------------------------------------------------------------------------
   2   4     53.420       2.800       4    2     -51.898      1.821      1.523      4.620
---------------------------------------------------------------------------------------
   2   5     39.391       4.510       5    2     -38.572     -2.007      0.820      2.503
---------------------------------------------------------------------------------------
   3   4    -24.329       7.528       4    3      24.755     -6.441      0.426      1.087
---------------------------------------------------------------------------------------
   4   5    -58.860      10.923       5    4      59.325     -9.457      0.465      1.466
---------------------------------------------------------------------------------------
   4   7     24.312     -15.004       7    4     -24.312     16.626     -0.000      1.622
---------------------------------------------------------------------------------------
   4   9     13.891      -2.419       9    4     -13.891      3.460      0.000      1.041
---------------------------------------------------------------------------------------
   5   6     41.052     -20.723       6    5     -41.052     25.516      0.000      4.793
---------------------------------------------------------------------------------------
   6  11      3.513       1.827      11    6      -3.500     -1.800      0.013      0.027
---------------------------------------------------------------------------------------
   6  12      6.144       1.691      12    6      -6.100     -1.600      0.044      0.091
---------------------------------------------------------------------------------------
   6  13     20.195      11.176      13    6     -19.888    -10.569      0.308      0.606
---------------------------------------------------------------------------------------
   7   8     -0.000     -20.280       8    7       0.000     20.942     -0.000      0.662
---------------------------------------------------------------------------------------
   7   9     24.312      15.419       9    7     -24.312    -14.586     -0.000      0.834
---------------------------------------------------------------------------------------
   9  14      8.703       0.628      14    9      -8.612     -0.434      0.091      0.194
---------------------------------------------------------------------------------------
  13  14      6.388       4.769      14   13      -6.288     -4.566      0.100      0.203
---------------------------------------------------------------------------------------
   Total Loss                                                           12.514     51.709
---------------------------------------------------------------------------------------
#######################################################################################
```

Fig. 4.1.1.3.2 - Output of the developed software for the example in Fig. 4.1.1.3.1

4.1.1.4 Transmission Line Capacities Effects

The capacities of the transmission lines in power systems play a crucial role on the evolution of cascading failures. As mentioned in Chapter 3 (Section 3.1), the energy flows satisfy Kirchhoff's laws. Thus, when a failure in the power grid occurs, the consequent redistribution of power flows may result in the overload of transmission lines due to the lack of capacity to accommodate all the power. To emphasize the importance of these capacities, we can take as example two different types of initial failures which highlight the effects resulting from the use of transmission lines with different capacities.

On the IEEE 14-bus system, the removal of the transmission line from bus 3 to bus 4 presents different results for different transmission line capacities as can be seen in Table AII.2 in Appendix II. For a tolerance of 15%, the NR method did not converge. With a 25% tolerance, after the initial failure, the transmission line from bus 2 to bus 3 was overloaded and failed. Consequently, due to the lack of active transmission lines connected to bus 3, this bus and its assigned router also failed.

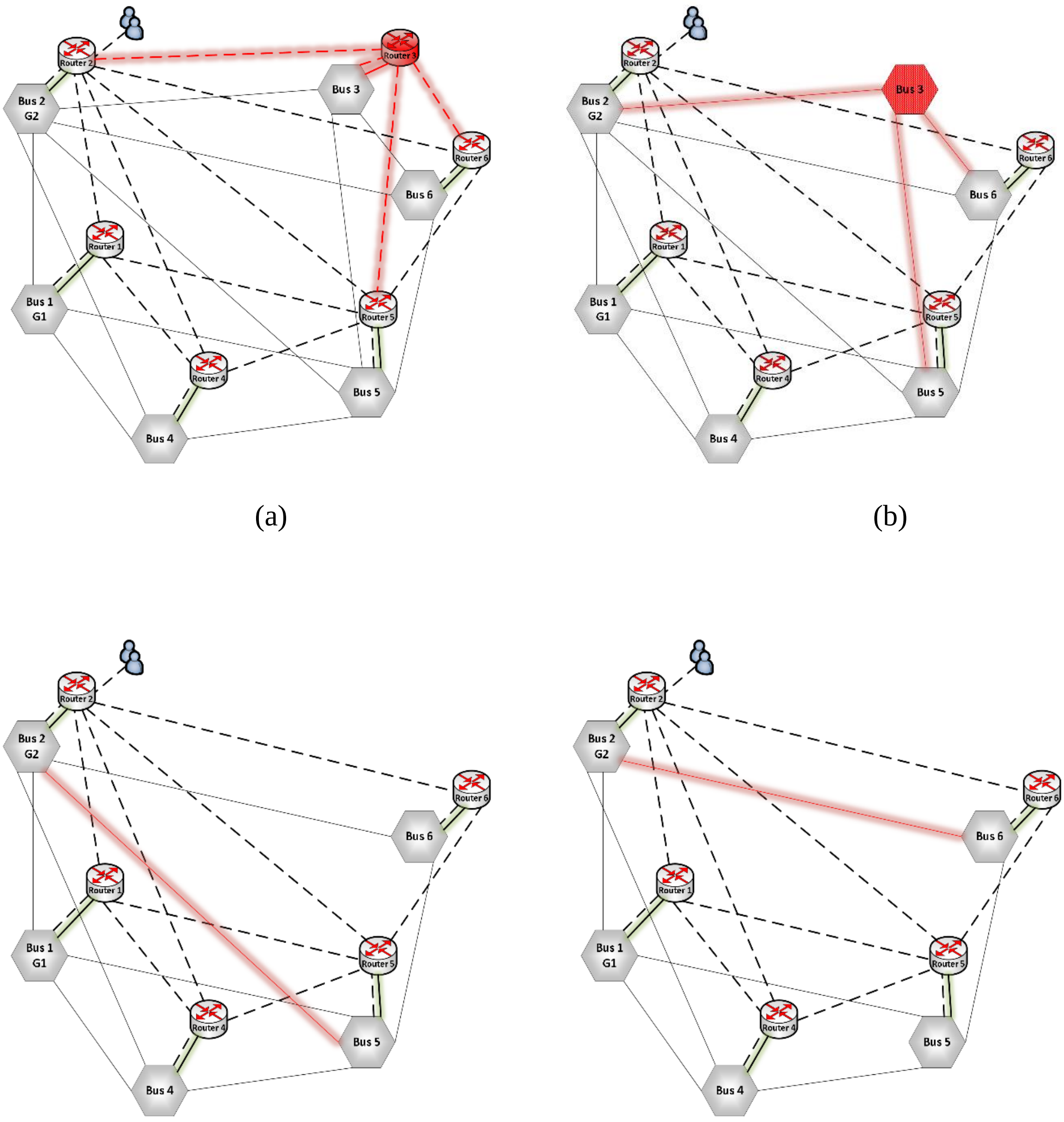
As far as the IEEE 6-bus system is concerned, the initial removal of bus 4 also has visible effects on the influence of the capacities of the transmission lines on the expansion of failures. The effects of this failure regarding component failures can be found in Table AII.3, in Appendix II.

4.1.2 Communication Network Failures

Since the communication networks can have several impacts in power grid operation [4], this section presents examples on the impact of failures occurring in the communication network components and will be divided into two subsections. The first subsection deals with communication nodes (routers), where a router belonging to the communication network fails. The second subsection deals with failures on communication connections from routers to assigned buses.

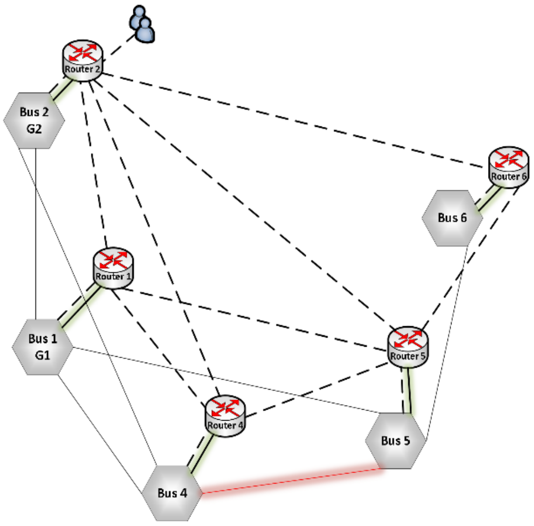
4.1.2.1. Router Failures

In the following example (Fig. 4.1.2.1.1), we initially considered a failure on the router number 3 of IEEE 6-bus system with a 50% tolerance of transmission lines capacities.

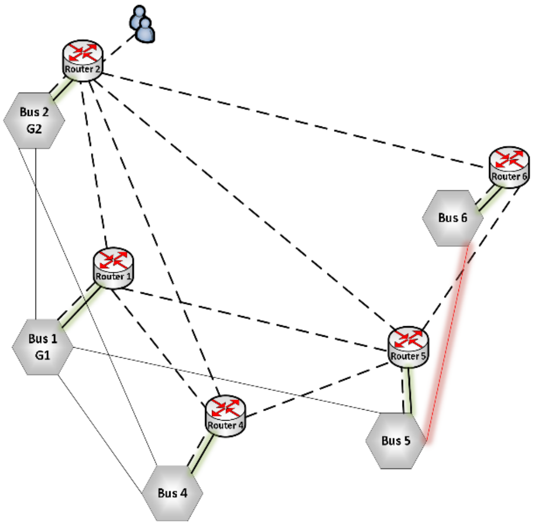


(a) (b)

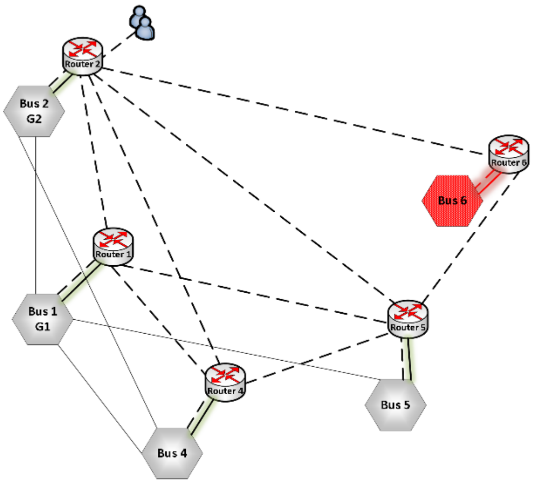
(c) (d)


Router 2
Bus 2
G2
Router 6
Bus 6
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

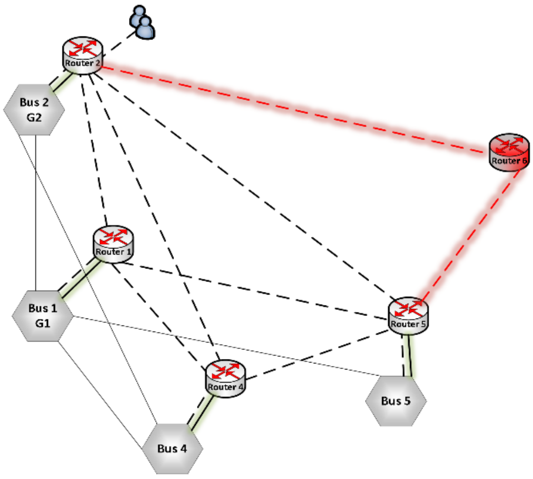
(e)


Router 2
Bus 2
G2
Router 6
Bus 6
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

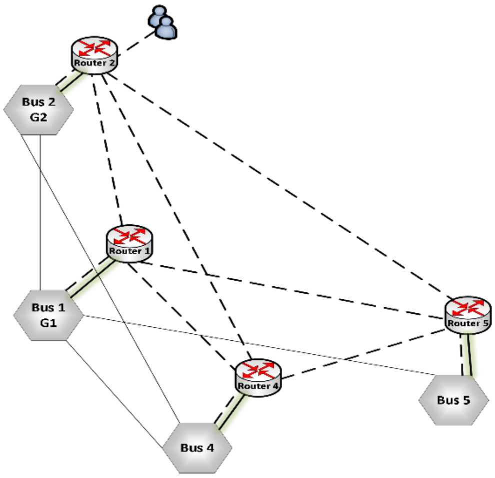
(f)


Router 2
Bus 2
G2
Router 6
Bus 6
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

(g)


Router 2
Bus 2
G2
Router 6
Router 1
Bus 1
G1
Router 5
Router 4
Bus 5
Bus 4

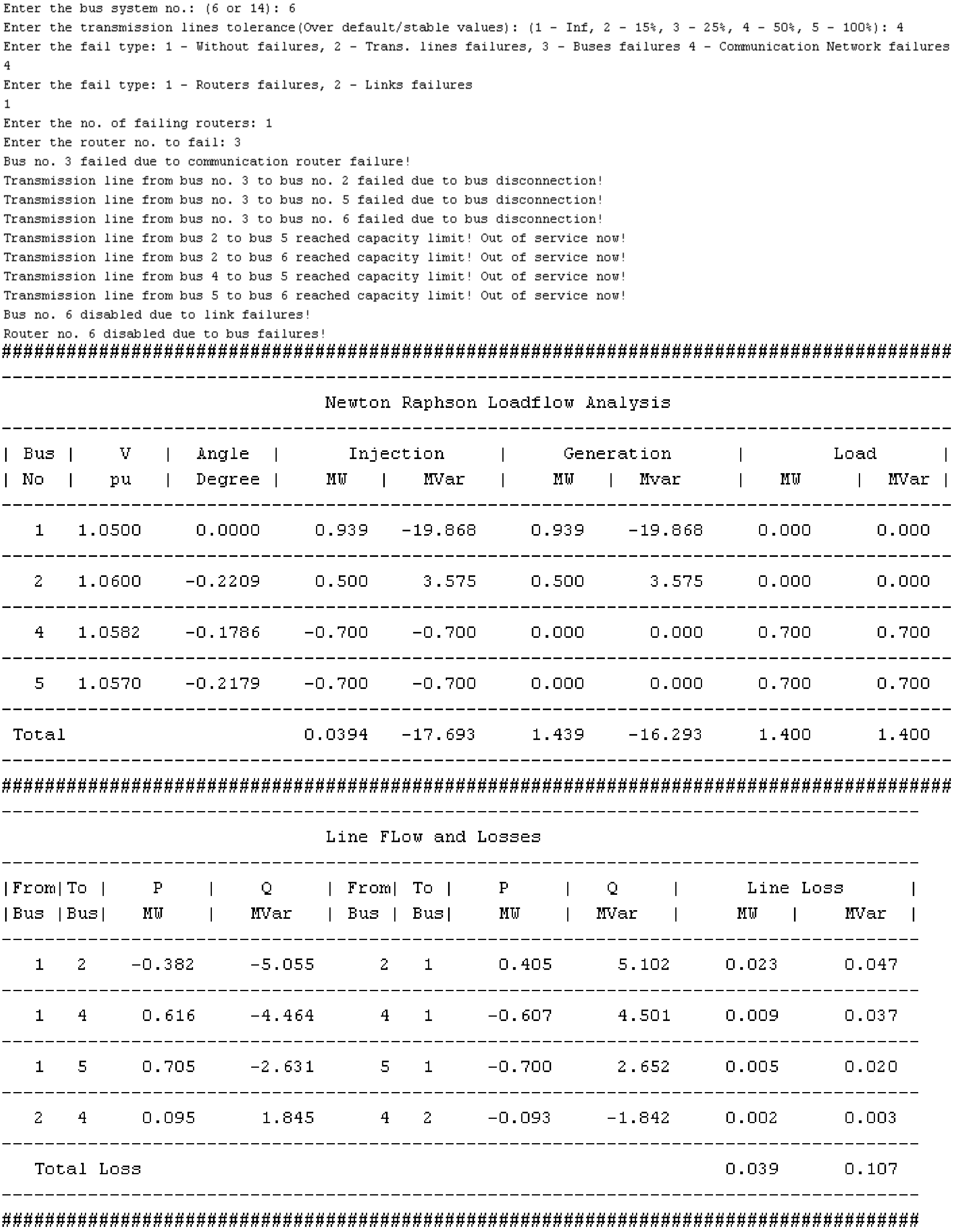
(h)



(i)

Fig. 4.1.2.1.1 - Schema of a cascading failure caused by a router failure

Fig. 4.1.2.1.1 shows a cascade of failures on the IEEE 6-bus system initiated by the loss of the communication router number 3 (Fig. 4.1.2.1.1(a)). From this failure, due to their interdependency, the bus 3 lost its communications and was shutdown (Fig. 4.1.2.1.1(b)). The shutdown of this bus, in turn led to the inactivity of the transmission lines that came out of it (transmission lines from bus 3 to buses 2, 5 and 6). After this, due to the redistribution of flows, some transmission lines overloaded (Figures 4.1.2.1.1(c), 4.1.2.1.1(d), 4.1.2.1.1(e) and 4.1.2.1.1(f)). Bus 6 lost all power links after the transmission line overloads and also went off (Fig. 4.1.2.1.1(g)). Consequently, router number 6 also fails due to insufficient power supply (Fig. 4.1.2.1.1(h)). The surviving part of the system is illustrated in Fig. 4.1.2.1.1(i). Power flows and other characteristics of the system after the end of the cascading events are shown in Fig. 4.1.2.1.2.

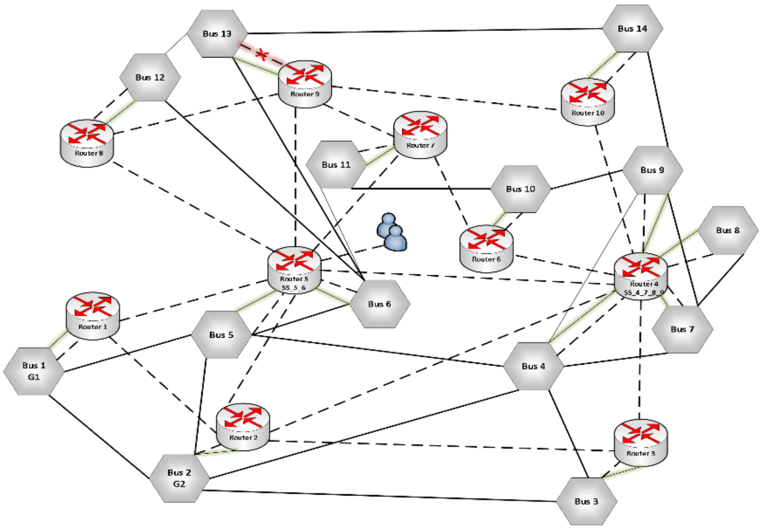


```
Enter the bus system no.: (6 or 14): 6
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 4
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
4
Enter the fail type: 1 - Routers failures, 2 - Links failures
1
Enter the no. of failing routers: 1
Enter the router no. to fail: 3
Bus no. 3 failed due to communication router failure!
Transmission line from bus no. 3 to bus no. 2 failed due to bus disconnection!
Transmission line from bus no. 3 to bus no. 5 failed due to bus disconnection!
Transmission line from bus no. 3 to bus no. 6 failed due to bus disconnection!
Transmission line from bus 2 to bus 5 reached capacity limit! Out of service now!
Transmission line from bus 2 to bus 6 reached capacity limit! Out of service now!
Transmission line from bus 4 to bus 5 reached capacity limit! Out of service now!
Transmission line from bus 5 to bus 6 reached capacity limit! Out of service now!
Bus no. 6 disabled due to link failures!
Router no. 6 disabled due to bus failures!
#########################################################################################
-----------------------------------------------------------------------------------------
                              Newton Raphson Loadflow Analysis
-----------------------------------------------------------------------------------------
| Bus |    V    |  Angle  |      Injection      |      Generation      |        Load      |
| No  |   pu    |  Degree |   MW    |   MVar    |    MW   |  Mvar      |   MW     |  MVar |
-----------------------------------------------------------------------------------------
   1   1.0500    0.0000     0.939   -19.868     0.939    -19.868     0.000      0.000
-----------------------------------------------------------------------------------------
   2   1.0600   -0.2209     0.500     3.575     0.500      3.575     0.000      0.000
-----------------------------------------------------------------------------------------
   4   1.0582   -0.1786    -0.700    -0.700     0.000      0.000     0.700      0.700
-----------------------------------------------------------------------------------------
   5   1.0570   -0.2179    -0.700    -0.700     0.000      0.000     0.700      0.700
-----------------------------------------------------------------------------------------
 Total                     0.0394   -17.693     1.439    -16.293     1.400      1.400
-----------------------------------------------------------------------------------------
#########################################################################################
--------------------------------------------------------------------------------------
                              Line FLow and Losses
--------------------------------------------------------------------------------------
|From|To |    P     |    Q     | From| To |    P     |   Q     |      Line Loss      |
|Bus |Bus|   MW     |   MVar   | Bus | Bus|   MW     |  MVar   |     MW   |   MVar   |
--------------------------------------------------------------------------------------
   1   2    -0.382     -5.055      2    1     0.405      5.102     0.023      0.047
--------------------------------------------------------------------------------------
   1   4     0.616     -4.464      4    1    -0.607      4.501     0.009      0.037
--------------------------------------------------------------------------------------
   1   5     0.705     -2.631      5    1    -0.700      2.652     0.005      0.020
--------------------------------------------------------------------------------------
   2   4     0.095      1.845      4    2    -0.093     -1.842     0.002      0.003
--------------------------------------------------------------------------------------
   Total Loss                                                      0.039      0.107
--------------------------------------------------------------------------------------
######################################################################################
```

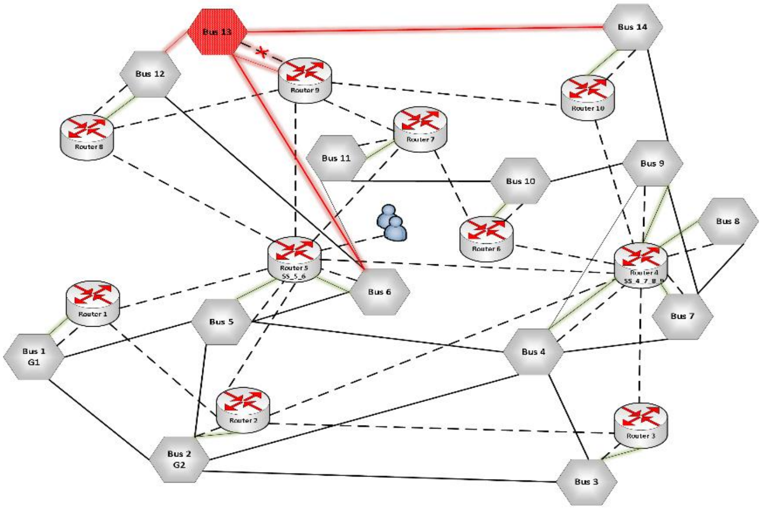
Fig. 4.1.2.1.2 - Output of the developed software for the example in Fig. 4.1.2.1.1

4.1.2.2. Failures on Communication Links Connecting Routers to Buses

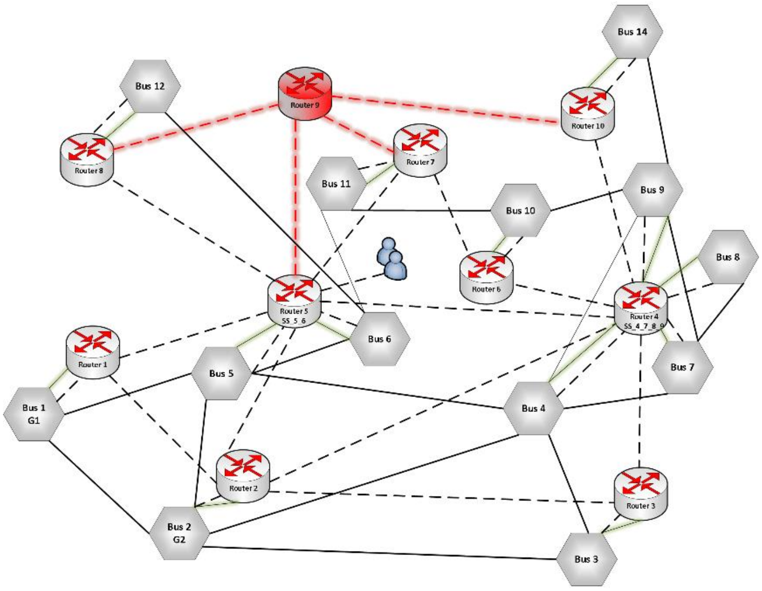
Here, we assume as initial failure a fault in a data link that establishes the communication from a router to a bus. The following example presents the cascading events resulting from the fault of the data link connecting router number 9 to bus 13 on IEEE 14-bus system.



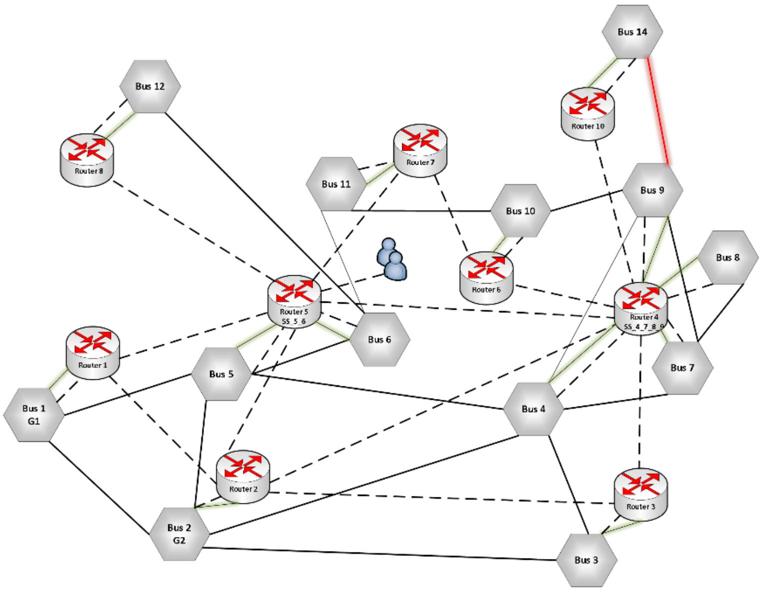
(a)



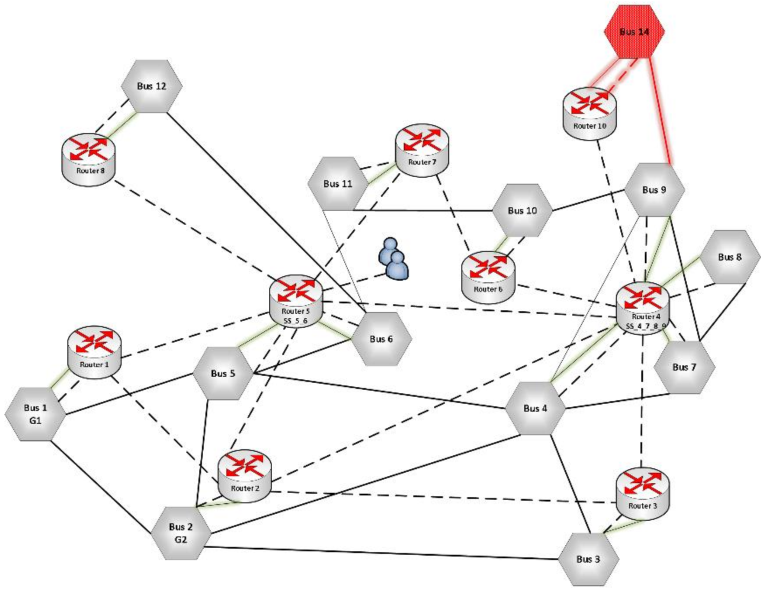
(b)


Bus 14
Bus 12
Router 9
Router 10
Router 8
Router 7
Bus 11
Bus 10
Bus 9
Bus 8
Router 6
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

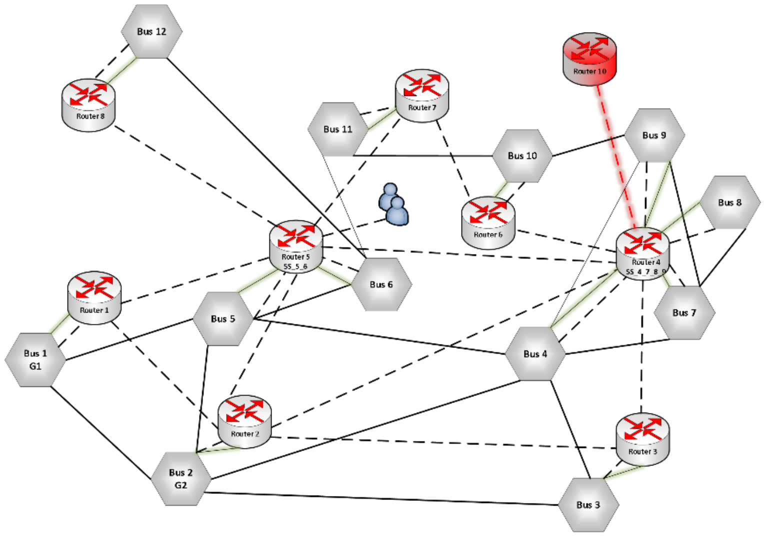
(c)


Bus 14
Bus 12
Router 10
Router 8
Router 7
Bus 11
Bus 10
Bus 9
Bus 8
Router 6
Router 5
SS_5_6
Router 4
SS_4_7_8_9
Bus 6
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

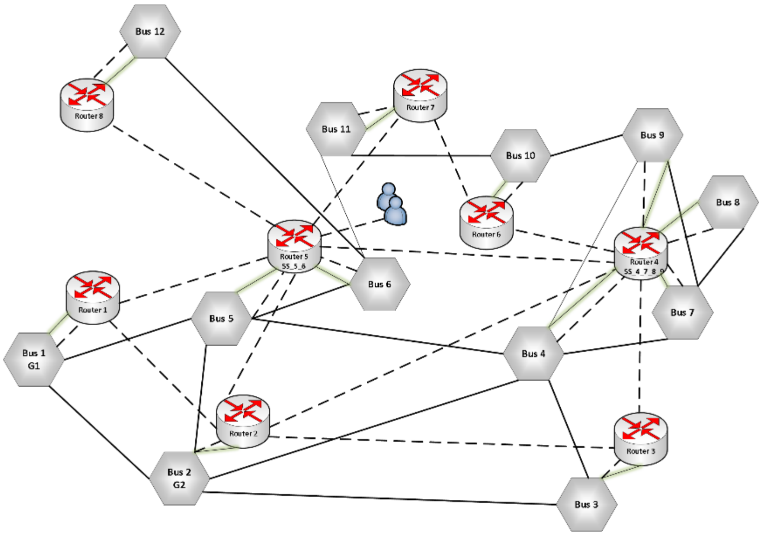
(d)


Bus 14
Bus 12
Router 10
Router 8
Router 7
Bus 11
Bus 9
Bus 10
Bus 8
Router 6
Router 5
SS_5_6
Bus 6
Router 4
SS_4_7_8_9
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

(e)


Bus 12
Router 10
Router 8
Router 7
Bus 11
Bus 9
Bus 10
Bus 8
Router 6
Router 5
SS_5_6
Bus 6
Router 4
SS_4_7_8_9
Router 1
Bus 5
Bus 7
Bus 1
G1
Bus 4
Router 2
Router 3
Bus 2
G2
Bus 3

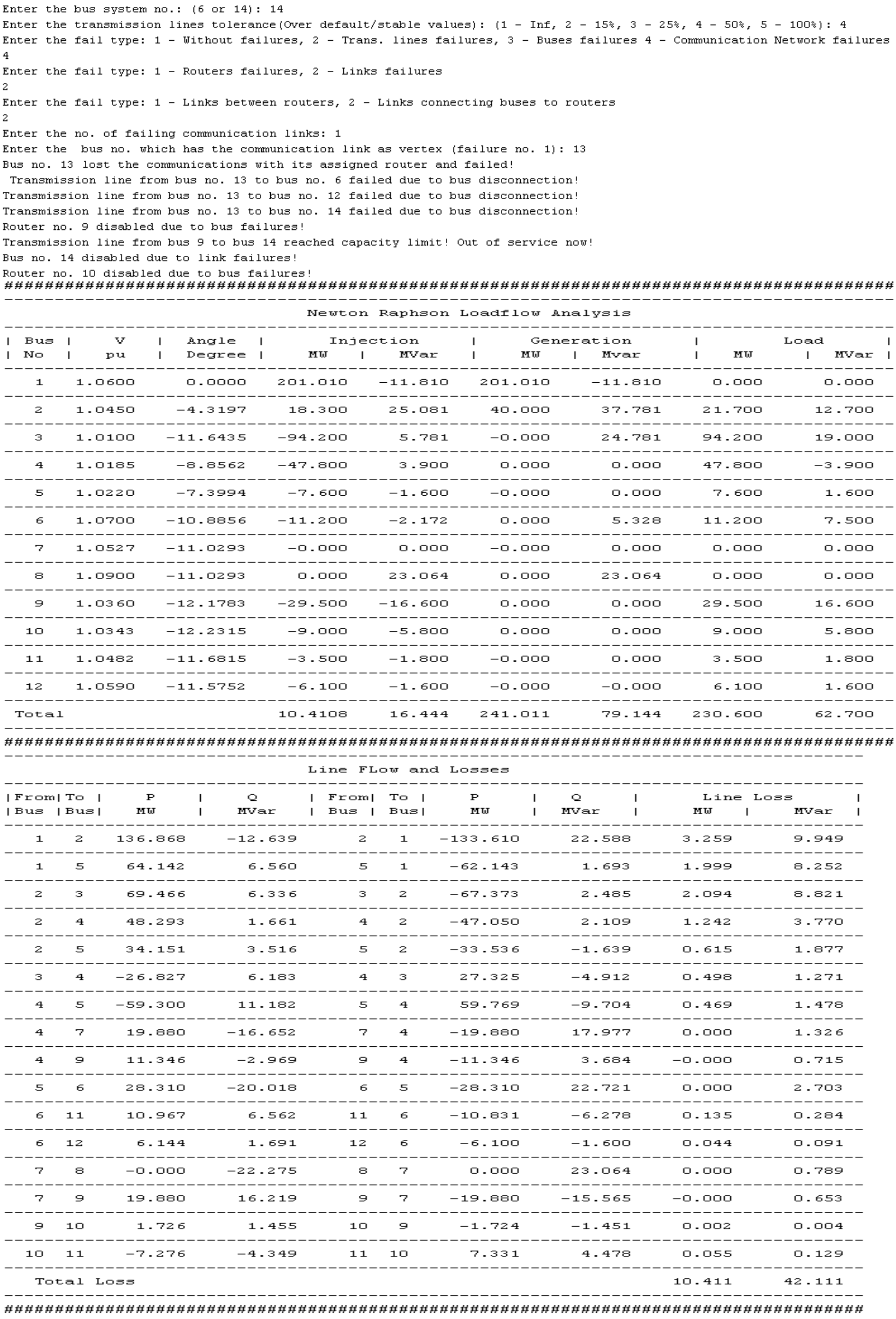
(f)



(g)

Fig. 4.1.2.2.1 - Schema of a cascading failure caused by a fault on a data link between a router and a bus

The initial failure is indicated using a red cross in Fig. 4.1.2.2.1(a). After this failure, bus 13 lost communications with the rest of the network and was unable to continue collecting essential information for its proper functioning which led to its failure (Fig. 4.1.2.2.1(b)). Consequently, router number 9 lost its power supply and was disabled (Fig. 4.1.2.2.1(c)). From the redistribution of power flows resulted the overload of transmission line connecting bus 9 to bus 14 (Fig. 4.1.2.2.1(d)). Hence, due to the lack of active transmission lines connected to bus 14, this bus was disconnected from the system as can be seen in Fig. 4.1.2.2.1(e). The lack of power supply to router number 10 led to its failure (Fig. 4.1.2.2.1(f)). The final state of the system is depicted in Fig. 4.1.2.2.1(g). Fig. 4.1.2.2.2 shows more detailed characteristics of the system final state as well as provide chronologic information about the outages.



```
Enter the bus system no.: (6 or 14): 14
Enter the transmission lines tolerance(Over default/stable values): (1 - Inf, 2 - 15%, 3 - 25%, 4 - 50%, 5 - 100%): 4
Enter the fail type: 1 - Without failures, 2 - Trans. lines failures, 3 - Buses failures 4 - Communication Network failures
4
Enter the fail type: 1 - Routers failures, 2 - Links failures
2
Enter the fail type: 1 - Links between routers, 2 - Links connecting buses to routers
2
Enter the no. of failing communication links: 1
Enter the  bus no. which has the communication link as vertex (failure no. 1): 13
Bus no. 13 lost the communications with its assigned router and failed!
 Transmission line from bus no. 13 to bus no. 6 failed due to bus disconnection!
Transmission line from bus no. 13 to bus no. 12 failed due to bus disconnection!
Transmission line from bus no. 13 to bus no. 14 failed due to bus disconnection!
Router no. 9 disabled due to bus failures!
Transmission line from bus 9 to bus 14 reached capacity limit! Out of service now!
Bus no. 14 disabled due to link failures!
Router no. 10 disabled due to bus failures!
#########################################################################################
-----------------------------------------------------------------------------------------
                              Newton Raphson Loadflow Analysis
-----------------------------------------------------------------------------------------
| Bus |    V    |  Angle  |      Injection      |     Generation      |        Load        |
| No  |   pu    |  Degree |    MW    |   MVar   |    MW    |   Mvar   |    MW     |  MVar  |
-----------------------------------------------------------------------------------------
   1   1.0600     0.0000   201.010   -11.810   201.010    -11.810     0.000      0.000
-----------------------------------------------------------------------------------------
   2   1.0450    -4.3197    18.300    25.081    40.000     37.781    21.700     12.700
-----------------------------------------------------------------------------------------
   3   1.0100   -11.6435   -94.200     5.781    -0.000     24.781    94.200     19.000
-----------------------------------------------------------------------------------------
   4   1.0185    -8.8562   -47.800     3.900     0.000      0.000    47.800     -3.900
-----------------------------------------------------------------------------------------
   5   1.0220    -7.3994    -7.600    -1.600    -0.000      0.000     7.600      1.600
-----------------------------------------------------------------------------------------
   6   1.0700   -10.8856   -11.200    -2.172     0.000      5.328    11.200      7.500
-----------------------------------------------------------------------------------------
   7   1.0527   -11.0293    -0.000     0.000    -0.000      0.000     0.000      0.000
-----------------------------------------------------------------------------------------
   8   1.0900   -11.0293     0.000    23.064     0.000     23.064     0.000      0.000
-----------------------------------------------------------------------------------------
   9   1.0360   -12.1783   -29.500   -16.600     0.000      0.000    29.500     16.600
-----------------------------------------------------------------------------------------
  10   1.0343   -12.2315    -9.000    -5.800     0.000      0.000     9.000      5.800
-----------------------------------------------------------------------------------------
  11   1.0482   -11.6815    -3.500    -1.800    -0.000      0.000     3.500      1.800
-----------------------------------------------------------------------------------------
  12   1.0590   -11.5752    -6.100    -1.600    -0.000     -0.000     6.100      1.600
-----------------------------------------------------------------------------------------
 Total                     10.4108    16.444   241.011     79.144   230.600     62.700
-----------------------------------------------------------------------------------------
#########################################################################################
--------------------------------------------------------------------------------------
                              Line FLow and Losses
--------------------------------------------------------------------------------------
|From|To |    P     |    Q     | From| To |    P     |   Q      |      Line Loss      |
|Bus |Bus|   MW     |   MVar   | Bus | Bus|   MW     |  MVar    |    MW    |   MVar   |
--------------------------------------------------------------------------------------
   1   2   136.868    -12.639      2    1   -133.610     22.588     3.259      9.949
--------------------------------------------------------------------------------------
   1   5    64.142      6.560      5    1    -62.143      1.693     1.999      8.252
--------------------------------------------------------------------------------------
   2   3    69.466      6.336      3    2    -67.373      2.485     2.094      8.821
--------------------------------------------------------------------------------------
   2   4    48.293      1.661      4    2    -47.050      2.109     1.242      3.770
--------------------------------------------------------------------------------------
   2   5    34.151      3.516      5    2    -33.536     -1.639     0.615      1.877
--------------------------------------------------------------------------------------
   3   4   -26.827      6.183      4    3     27.325     -4.912     0.498      1.271
--------------------------------------------------------------------------------------
   4   5   -59.300     11.182      5    4     59.769     -9.704     0.469      1.478
--------------------------------------------------------------------------------------
   4   7    19.880    -16.652      7    4    -19.880     17.977     0.000      1.326
--------------------------------------------------------------------------------------
   4   9    11.346     -2.969      9    4    -11.346      3.684    -0.000      0.715
--------------------------------------------------------------------------------------
   5   6    28.310    -20.018      6    5    -28.310     22.721     0.000      2.703
--------------------------------------------------------------------------------------
   6  11    10.967      6.562     11    6    -10.831     -6.278     0.135      0.284
--------------------------------------------------------------------------------------
   6  12     6.144      1.691     12    6     -6.100     -1.600     0.044      0.091
--------------------------------------------------------------------------------------
   7   8    -0.000    -22.275      8    7      0.000     23.064     0.000      0.789
--------------------------------------------------------------------------------------
   7   9    19.880     16.219      9    7    -19.880    -15.565    -0.000      0.653
--------------------------------------------------------------------------------------
   9  10     1.726      1.455     10    9     -1.724     -1.451     0.002      0.004
--------------------------------------------------------------------------------------
  10  11    -7.276     -4.349     11   10      7.331      4.478     0.055      0.129
--------------------------------------------------------------------------------------
   Total Loss                                                     10.411     42.111
--------------------------------------------------------------------------------------
######################################################################################
```

Fig. 4.1.2.2.2 - Output of the developed software for the example in Fig. 4.1.2.2.1

Chapter 5 – Conclusion

This work analyses the effects in terms of failure propagation of the incorporation of a communication network infrastructure into a power grid. The deployed model exposes the smart grid vulnerabilities due to the interdependency of power and communication networks and also due to the systems dynamics. The simulations of two different standard IEEE bus systems in the presence of communications were conducted and the effects of disturbances and failures were also tested and analysed in the experiments. The communication network plays a crucial role in the reliability of the power systems and is indispensable for its proper functioning.

As an outcome of the presented model, we can conclude that the interdependency between the two networks has a huge impact on network resilience. However, the transmission line capacities are also a determining factor in the extension of the power outages. As proved, higher capacities can significantly reduce the effects of cascading failures.

5.1 Future Work

There are several lines of research arising from this work that may be of interest to future work. One possibility would be to consider the capacities of communication lines, which, with a centralized control center, presented scalability problems in [26], when data flows are high. In this case, the decentralization of the control center may be the best decision.

Since the power flow convergence issues increase with the systems size, it can be useful to have an appropriate reactive power planning strategy, as done in [31]. Thus, it will be possible to apply these cascading failures studies to larger systems such as intercontinental grids.

Finally, the incorporation of DER into the model may be a future development since the local distributed power generation, even when using only a few local generators, can reduce the occurrence of cascading failures, as proved in [36].

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Appendix I – IEEE Bus System Data

The detailed characteristics of the fictitious test cases addressed in Chapter 3 (Section 3.1) are presented in this Appendix. Systems schematics are depicted in Figures AI.1 and AI.2 , for IEEE 6-bus and 14-bus systems, respectively. The following tables contain information about the busbars and transmission lines of each system. The data used to form the test systems models is on 100 MVA base and is given below:

IEEE 6-Bus System

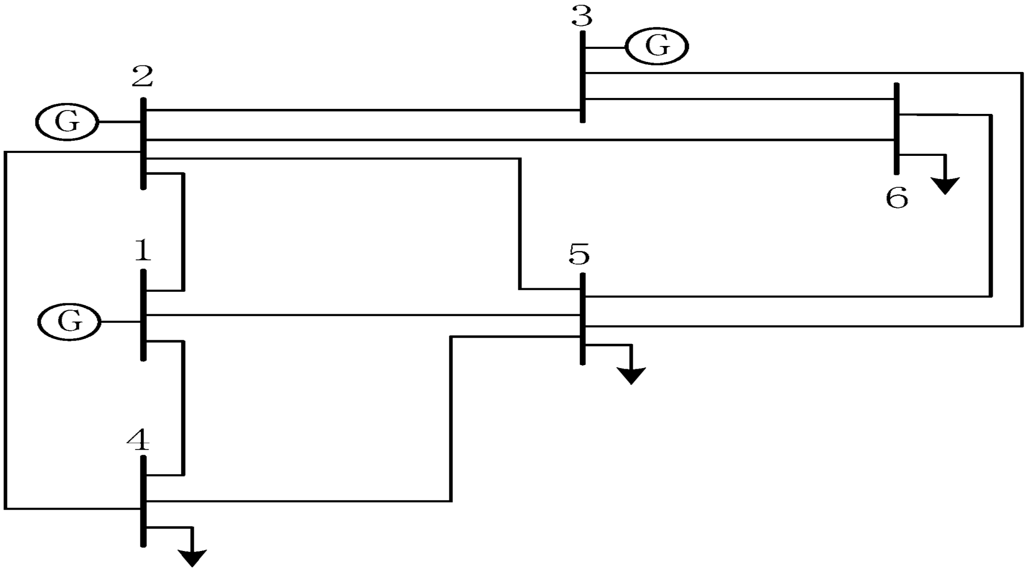

Fig. AI.1 – IEEE 6-bus system schematic [37]

Table AI.1 – Line data of IEEE 6-bus system

Line No.	From Bus	To Bus	Line Impedance (P.U.)		Half Line Charging Susceptance (P.U.)
			Resistance	Reactance	
1	1	2	0.10	0.20	0.02
2	1	4	0.05	0.20	0.02
3	1	5	0.08	0.30	0.03
4	2	3	0.05	0.25	0.03
5	2	4	0.05	0.10	0.01
6	2	5	0.10	0.30	0.02
7	2	6	0.07	0.20	0.025
8	3	5	0.12	0.26	0.025
9	3	6	0.02	0.10	0.01
10	4	5	0.20	0.40	0.04
11	5	6	0.10	0.30	0.03

Table AI.2 – IEEE 6-bus system modeled MVA limits

Line		Stable State MVA	Modeled MVA Limits			
From bus	To bus		Tol. 15%	Tol. 25%	Tol. 50%	Tol. 100%
1	2	15.5868	17.9249	19.4836	23.3803	31.1737
1	4	14.2662	16.4061	17.8328	21.3993	28.5324
1	5	12.3770	14.2335	15.4712	18.5655	24.7540
2	3	0.1031	0.1186	0.1289	0.1547	0.2062
2	4	4.9007	5.6358	6.1259	7.3510	9.8014
2	5	1.1126	1.2795	1.3907	1.6689	2.2252
2	6	2.1388	2.4596	2.6735	3.2082	4.2776
3	5	1.2504	1.4380	1.5631	1.8757	2.5009
3	6	4.5265	5.2055	5.6582	6.7898	9.0531
4	5	1.9799	2.2769	2.4749	2.9699	3.9598
5	6	0.3412	0.3924	0.4265	0.5118	0.6824

Table AI.3 - Bus data of IEEE 6-bus system

Bus No.	Type	Bus Voltage		Generation		Load		Reactive Power Limits	
		Magnitude (P.U.)	Angle (degree)	Real Power (MW)	Reactive Power (MVAR)	Real Power (MW)	Reactive Power (MVAR)	Q_{max} (MVAR)	Q_{min} (MVAR)
1	1	1.05	0	0.0	0.0	0.0	0.0	0.0	0.0
2	2	1.05	0	0.5	0.0	0.0	0.0	-0.5	1.0
3	2	1.07	0	0.6	0.0	0.0	0.0	-0.5	1.5
4	0	1.00	0	0.0	0.0	0.7	0.7	0.0	0.0
5	0	1.00	0	0.0	0.0	0.7	0.7	0.0	0.0
6	0	1.00	0	0.0	0.0	0.7	0.7	0.0	0.0

IEEE 14-Bus System

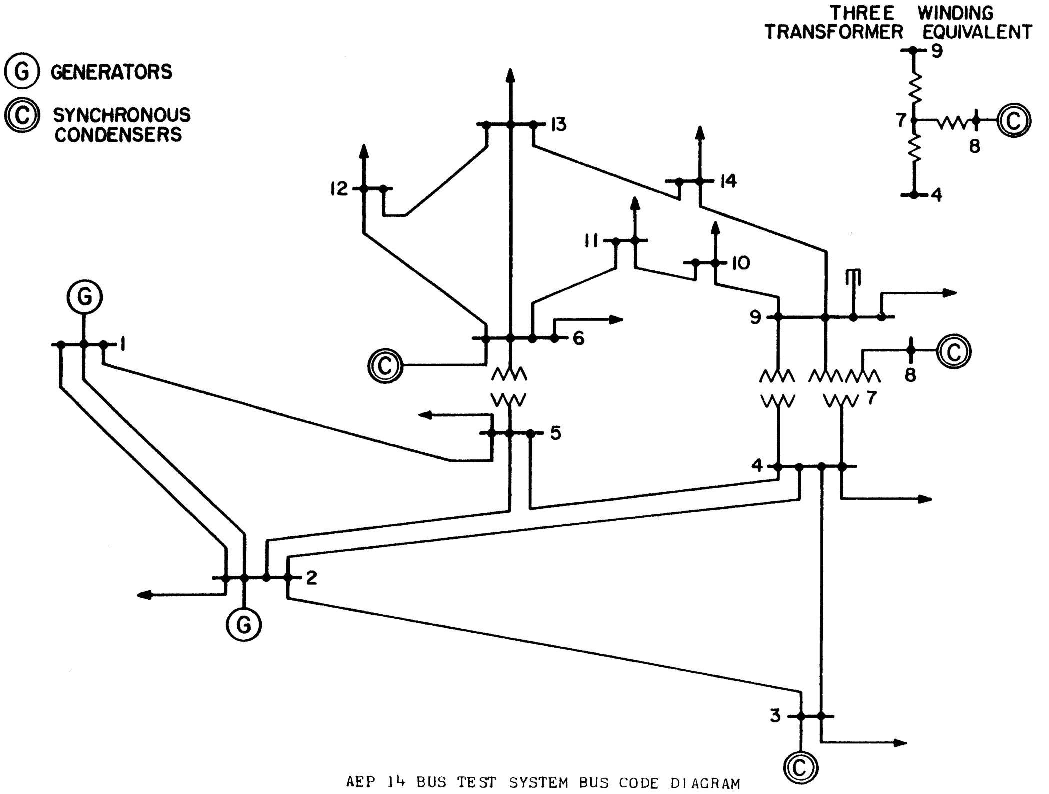

Fig. AI.2 – IEEE 14-bus system schematic [38]

Table AI.4 - Line data of IEEE 14-bus system

Line No.	From Bus	To Bus	Line Impedance (P.U.)		Half Line Charging Susceptance (P.U.)
			Resistance	Reactance	
1	1	2	0.01938	0.05917	0.0264
2	1	5	0.05403	0.22304	0.0246
3	2	3	0.04699	0.19797	0.0219
4	2	4	0.05811	0.17632	0.0170
5	2	5	0.05695	0.17388	0.0173
6	3	4	0.06701	0.17103	0.0064
7	4	5	0.01335	0.04211	0.0
8	4	7	0.0	0.20912	0.0
9	4	9	0.0	0.55618	0.0
10	5	6	0.0	0.25202	0.0
11	6	11	0.09498	0.19890	0.0
12	6	12	0.12291	0.25581	0.0
13	6	13	0.06615	0.13027	0.0
14	7	8	0.0	0.17611	0.0
15	7	9	0.0	0.11001	0.0
16	9	10	0.03181	0.08450	0.0
17	9	14	0.12711	0.27038	0.0
18	10	11	0.08205	0.19207	0.0
19	12	13	0.22092	0.19988	0.0
20	13	14	0.17093	0.34802	0.0

Table AI.5 – IEEE 14-bus system transformer tap setting data

From Bus	To Bus	Tap Setting Value (p.u)
4	7	0.978
4	9	0.969
5	6	0.932

Table AI.6 – IEEE 14-bus system modeled MVA limits

Line		Stable State MVA	Modeled MVA Limits			
From bus	To bus		Tol. 15%	Tol. 25%	Tol. 50%	Tol. 100%
1	2	158.0504	181.7580	197.5630	237.0756	316.1008
1	5	75.9332	87.3232	94.9165	113.8998	151.8664
2	3	73.6356	84.6810	92.0445	110.4534	147.2712
2	4	56.0200	64.4230	70.0250	84.0300	112.0400
2	5	42.0008	48.3010	52.5011	63.0013	84.0017
3	4	24.4784	28.1502	30.5980	36.7176	48.9558
4	5	60.9011	70.0363	76.1264	91.3517	121.8023
4	7	32.1370	36.9575	40.1712	48.2055	64.2740
4	9	15.9559	18.3493	19.9449	23.9339	31.9119
5	6	53.0494	61.0069	66.3118	79.5742	106.0989
6	11	12.1592	13.9831	15.1990	18.2388	24.3184
6	12	8.6672	9.9673	10.8340	13.0008	17.3345
6	13	20.8776	24.0092	26.0970	31.3164	41.7552
7	8	21.0303	24.1849	26.2879	31.5455	42.0607
7	9	30.8468	35.4739	38.5585	46.2703	61.6937
9	10	4.4849	5.1577	5.6062	6.7274	8.9699
9	14	8.6428	9.8307	10.8035	12.9642	17.2855
10	11	8.2798	9.5217	10.3497	12.4196	16.5595
12	13	2.3519	2.7046	2.9398	3.5278	4.7037
13	14	8.2187	9.4515	10.2733	12.3280	16.4373

Table AI.7 – IEEE 14-bus system bus data

Bus No.	Type	Bus Voltage		Generation		Load		Reactive Power Limits	
		Magnitude (P.U.)	Angle (degree)	Real Power (MW)	Reactive Power (MVAR)	Real Power (MW)	Reactive Power (MVAR)	Q_{max} (MVAR)	Q_{min} (MVAR)
1	1	1.060	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	2	1.045	0.0	40.0	42.4	21.7	12.7	-40.0	50.0
3	2	1.010	0.0	0.0	23.4	94.2	19.0	0.0	40.0
4	0	1.0	0.0	0.0	0.0	47.8	-3.9	0.0	0.0
5	0	1.0	0.0	0.0	0.0	7.6	1.6	0.0	0.0
6	2	1.070	0.0	0.0	12.2	11.2	7.5	-6.0	24.0
7	0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	2	1.090	0.0	0.0	17.4	0.0	0.0	-6.0	24.0
9	0	1.0	0.0	0.0	0.0	29.5	16.6	0.0	0.0
10	0	1.0	0.0	0.0	0.0	9.0	5.8	0.0	0.0
11	0	1.0	0.0	0.0	0.0	3.5	1.8	0.0	0.0
12	0	1.0	0.0	0.0	0.0	6.1	1.6	0.0	0.0
13	0	1.0	0.0	0.0	0.0	13.5	5.8	0.0	0.0
14	0	1.0	0.0	0.0	0.0	14.9	5.0	0.0	0.0

Appendix II – Tables of Results

This appendix is composed of several tables containing the fault record for different type of initial failures. The component failures for different transmission line capacities are shown by order of event. When power flow convergence is not reached or the entire system fails, the results are presented in shaded red. For detailed information about the power flows and the voltages and angles of the buses, it's necessary to run the software with the specified conditions for each case. We use "X→Y" to indicate that transmission line from bus X to bus Y failed. When a bus fails, its attached lines also fails, but due to the lack of space those lines were hidden in the following tables.

Table AII.1 – IEEE 6-bus system single line failures results

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
1	2	Converged Without Faults	Converged Without Faults	Converged Without Faults	Converged Without Faults
1	4	Convergence not verified	Convergence not verified	Converged 2→3	Converged Without Faults
1	5	2→3 2→6 4→5 2→4 5→6	Convergence not verified	Convergence not verified	Convergence not verified
2	3	Converged Without Faults	Converged Without Faults	Converged Without Faults	Converged Without Faults
2	4	Converged 2→3 4→5 5→6	Converged 2→3 4→5 5→6	Converged 2→3 4→5 5→6	Converged 2→3 5→6 2→5
2	5	Converged 2→3 2→6 4→5 5→6	Converged 2→3 2→6 4→5 5→6	Converged 2→3 2→6 4→5 5→6	Converged 2→3 2→6 4→5 5→6

Table AII.1 (cont.)

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
2	6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6
3	5	Convergence not verified	Converged 2→3 5→6	Converged 2→3 5→6	Converged 2→3 5→6
3	6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6
4	5	Convergence not verified	Convergence not verified	Converged 2→3 2→6 5→6	Converged 2→3 2→6 5→6
5	6	Converged 2→3 2→5 4→5	Converged 2→3 2→5 4→5	Converged 2→3 2→5 4→5	Converged 2→3 2→5

Table AII.2 – IEEE 14-bus system single line failures results

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
1	2	1→5 Slack bus failed	1→5 Slack bus failed	1→5 Slack bus failed	1→5 Slack bus failed
1	5	1→2 Slack bus failed	1→2 Slack bus failed	1→2 Slack bus failed	Converged Without Faults
2	3	1→5 1→2 Slack bus failed	1→5 1→2 Slack bus failed	2→4 1→5 1→2 Slack bus failed	Converged 3→4 Bus no. 3 disabled Router no. 3 disabled
2	4	1→5 1→2 Slack bus failed	2→5 1→5 1→2 Slack bus failed	2→5 1→5 1→2 Slack bus failed	Converged Without Faults
2	5	1→5 1→2 Slack bus failed	2→4 1→5 1→2 Slack bus failed	Converged Without Faults	Converged Without Faults
3	4	Convergence not verified	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled	Converged Without Faults	Converged Without Faults
4	5	Convergence not verified	Convergence not verified	Convergence not verified	Converged Without Faults
4	7	Convergence not verified	Convergence not verified	Convergence not verified	Converged Without Faults
4	9	Convergence not verified	Convergence not verified	Converged Without Faults	Converged Without Faults
5	6	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
6	11	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified

Table AII.2 (cont.)

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
6	12	Convergence not verified	Convergence not verified	Converged 12→13 Bus no. 12 disabled Router no. 8 disabled	Converged 12→13 Bus no. 12 disabled Router no. 8 disabled
6	13	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
7	8	Convergence not verified	Converged Bus no. 8 disabled	Converged Bus no. 8 disabled	Converged Bus no. 8 disabled
7	9	4→9 2→5 1→5 1→2 Slack bus failed	Convergence not verified	Convergence not verified	Convergence not verified
9	10	Convergence not verified	Converged 10→11 Bus no. 10 disabled Router no. 6 disabled	Converged Without Faults	Converged Without Faults
9	14	Convergence not verified	Convergence not verified	Convergence not verified	Converged 9→10
10	11	Converged 9→10 Bus no. 10 disabled Router no. 6 disabled	Converged 9→10 Bus no. 10 disabled Router no. 6 disabled	Converged 9→10 Bus no. 10 disabled Router no. 6 disabled	Converged 9→10 Bus no. 10 disabled Router no. 6 disabled
12	13	Converged Without Faults	Converged Without Faults	Converged Without Faults	Converged Without Faults

Table AII.2 (cont.)

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
13	14	Convergence not verified	Converged 9→14 Bus no. 14 disabled Router no. 10 disabled	Converged 9→14 Bus no. 14 disabled Router no. 10 disabled	Converged Without Faults

Table AII.3 – IEEE 6-bus system single bus failures results

Bus Failure Bus No.	Components failures post initial failure			
	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
1	Slack bus is protected	Slack bus is protected	Slack bus is protected	Slack bus is protected
2	Control center failed. The entire system failed.	Control center failed. The entire system failed.	Control center failed. The entire system failed.	Control center failed. The entire system failed.
3	Converged Router no. 3 disabled 2→5 2→6 4→5 5→6 Bus no. 6 disabled Router no. 6 disabled	Converged Router no. 3 disabled 2→5 2→6 4→5 5→6 Bus no. 6 disabled Router no. 6 disabled	Converged Router no. 3 disabled 2→5 2→6 4→5 5→6 Bus no. 6 disabled Router no. 6 disabled	Converged Router no. 3 disabled 2→5 2→6 5→6 Bus no. 6 disabled Router no. 6 disabled
4	Converged Router no. 4 disabled 2→3 5→6 2→5	Converged Router no. 4 disabled 2→3 5→6	Converged Router no. 4 disabled 5→6	Converged Router no. 4 disabled 5→6
5	Converged Router no. 5 disabled	Converged Router no. 5 disabled	Converged Router no. 5 disabled	Converged Router no. 5 disabled
6	Converged Router no. 6 disabled 2→3 2→5 3→5 Bus no. 3 disabled Router no. 3 disabled	Converged Router no. 6 disabled 2→3 2→5 3→5 Bus no. 3 disabled Router no. 3 disabled	Converged Router no. 6 disabled 2→3 2→5 3→5 Bus no. 3 disabled Router no. 3 disabled	Converged Router no. 6 disabled 2→3 2→5 3→5 Bus no. 3 disabled Router no. 3 disabled

Table AII.4 – IEEE 14-bus system single bus failures results

Bus Failure	Components failures post initial failure			
Bus No.	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
1	Slack bus is protected	Slack bus is protected	Slack bus is protected	Slack bus is protected
2	Router no. 2 disabled 1→5 Slack bus failed	Router no. 2 disabled 1→5 Slack bus failed	Router no. 2 disabled 1→5 Slack bus failed	Router no. 2 disabled 1→5 Slack bus failed
3	Convergence not verified	Converged Router no. 3 disabled	Converged Router no. 3 disabled	Converged Router no. 3 disabled
4	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
5	1→2 Slack bus failed	1→2 Slack bus failed	1→2 Slack bus failed	Convergence not verified
6	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
7	4→9 2→5 1→5 1→2 Slack bus failed	Convergence not verified	Convergence not verified	Convergence not verified
8	Convergence not verified	Converged Without Faults	Converged Without Faults	Converged Without Faults
9	Convergence not verified	Convergence not verified	Convergence not verified	Converged Without Faults
10	Converged Router no. 6 disabled	Converged Router no. 6 disabled	Converged Router no. 6 disabled	Converged Router no. 6 disabled
11	Converged Router no. 7 disabled 9→10 Bus no.10 disabled Router no. 6 disabled	Converged Router no. 7 disabled 9→10 Bus no.10 disabled Router no. 6 disabled	Converged Router no. 7 disabled 9→10 Bus no.10 disabled Router no. 6 disabled	Converged Router no. 7 disabled 9→10 Bus no.10 disabled Router no. 6 disabled
12	Converged Router no. 8 disabled	Converged Router no. 8 disabled	Converged Router no. 8 disabled	Converged Router no. 8 disabled

Table AII.4 (cont.)

Bus Failure	Components failures post initial failure			
Bus No.	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
13	Convergence not verified	Convergence not verified	Router no. 9 disabled 9→14 Bus no. 14 disabled Router no. 10 disabled	Converged Router no. 9 disabled
14	Converged Router no. 10 disabled	Converged Router no. 10 disabled	Converged Router no. 10 disabled	Converged Router no. 10 disabled

Table AII.5 – IEEE 6-bus system multiline failures results

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
1 1	2 4	5→1 Slack Bus Failed	5→1 Slack Bus Failed	5→1 Slack Bus Failed	Converged 5→6
1 1	2 5	1→4 Slack Bus Failed	1→4 Slack Bus Failed	2→3 2→6 3→5 4→5	Convergence not verified
1 1	4 5	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
2 2	3 4	Converged 4→5 5→6	Converged 4→5 5→6	Converged 4→5 5→6	Converged 5→6 2→5
2 2	3 5	Converged 2→6 4→5 5→6	Converged 2→6 4→5 5→6	Converged 2→6 4→5 5→6	Converged 2→6 4→5 5→6

Table AII.5 (cont.)

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
2 2	3 6	Converged 2→5 4→5 5→6	Converged 2→5 4→5 5→6	Converged 2→5 4→5 5→6	Converged 2→5 4→5 5→6
2 2	4 5	Converged 2→3 2→6 4→5 5→6	Converged 2→3 2→6 4→5 5→6	Converged 2→3 2→6 4→5 5→6	Converged 2→3 2→6 5→6
2 2	5 6	Converged 2→3 4→5 5→6	Converged 2→3 4→5 5→6	Converged 2→3 4→5 5→6	Converged 2→3 4→5 5→6
2 2	4 6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 4→5 5→6	Converged 2→3 2→5 5→6
3 3	5 6	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled
3 4	5 5	Converged 2→3 5→6	Converged 2→3 5→6	Converged 2→3	Converged 2→3
3 4	6 5	Converged 2→3 5→6	Converged 2→3 5→6	Converged 2→3 5→6	Converged 2→3 5→6
4 5	5 6	Converged 2→5	Converged	Converged	Converged
3 5	6 6	Converged 2→3 2→5 4→5	Converged 2→3 2→5 4→5	Converged 2→3 2→5 4→5	Converged 2→3 2→5
1 5	5 6	Converged 2→3	Converged 2→3	Converged 2→3	Converged 2→3

Table AII.5 (cont.)

Line Failure		Components failures post initial failure			
From bus	To bus	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
3 3	5 6	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled	Converged 2→3 Bus no. 3 disabled Router no. 3 disabled
3 4	5 5	Converged 2→3 5→6	Converged 2→3 5→6	Converged 2→3	Converged 2→3
3 4	6 5	Converged 2→3 5→6	Converged 2→3 5→6	Converged 2→3 5→6	Converged 2→3 5→6
4 5	5 6	Converged 2→5	Converged	Converged	Converged
3 5	6 6	Converged 2→3 2→5 4→5	Converged 2→3 2→5 4→5	Converged 2→3 2→5 4→5	Converged 2→3 2→5
1 5	5 6	Converged 2→3	Converged 2→3	Converged 2→3	Converged 2→3
2 5	3 6	Converged 2→5 4→5	Converged 2→5 4→5	Converged 2→5 4→5	Converged 2→5
2 2 3	4 6 5	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
2 4 5	4 5 6	Converged 3→5	Converged	Converged	Converged
2 2 4 5	3 4 5 6	Converged	Converged	Converged	Converged
1 1 5	2 4 6	Converged	Converged	Converged	Converged

Table AII.6 – IEEE 14-bus system multiline failures results

Line Failure		Components failures post initial failure			
From bus	To bus	Tolerance =15%	25%	50%	100%
5 4	4 3	Convergence not verified	Convergence not verified	Convergence not verified	Converged Without faults
2 4	3 5	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
9 13	10 14	Convergence not verified	10→11 Bus no. 10 disabled Router no. 6 disabled	Converged Without faults	Converged Without faults
6 9	11 10	Convergence not verified	Convergence not verified	Convergence not verified	Convergence not verified
3 6	4 12	Convergence not verified	Convergence not verified	12→13 Bus no. 12 disabled Router no. 8 disabled	12→13 Bus no. 12 disabled Router no. 8 disabled
13 12	14 13	Convergence not verified	9→14 Bus no. 14 disabled Router no. 10 disabled	9→14 Bus no. 14 disabled Router no. 10 disabled	Converged Without faults
3 10 13	4 11 14	Convergence not verified	Convergence not verified	9→10 Bus no. 10 disabled Router no. 6 disabled	9→10 Bus no. 10 disabled Router no. 6 disabled

Table AII.7 – IEEE 6-bus system router failures results

Router No.	Components failures post initial failure			
	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
1	Slack bus failed	Slack bus failed	Slack bus failed	Slack bus failed
2	Control center failed	Control center failed	Control center failed	Control center failed
3	Bus no. 3 failed 2→5 2→6 4→5 5→6 Bus no. 6 failed Router no. 6 failed	Bus no. 3 failed 2→5 2→6 4→5 5→6 Bus no. 6 failed Router no. 6 failed	Bus no. 3 failed 2→5 2→6 4→5 5→6 Bus no. 6 failed Router no. 6 failed	Bus no. 3 failed 2→5 2→6 5→6 Bus no. 6 failed Router no. 6 failed
4	Bus no. 4 failed 2→3 5→6 2→5	Bus no. 4 failed 2→3 5→6	Bus no. 4 failed 5→6	Bus no. 4 failed 5→6
5	Bus no. 5 failed	Bus no. 5 failed	Bus no. 5 failed	Bus no. 5 failed
6	Bus no. 6 failed 2→3 2→5 3→5 Bus no. 3 failed Router no. 3 failed	Bus no. 6 failed 2→3 2→5 3→5 Bus no. 3 failed Router no. 3 failed	Bus no. 6 failed 2→3 2→5 3→5 Bus no. 3 failed Router no. 3 failed	Bus no. 6 failed 2→3 2→5 3→5 Bus no. 3 failed Router no. 3 failed

Table AII.8 – IEEE 14-bus system router failures results

Router No.	Components failures post initial failure			
	15% Tolerance	25% Tolerance	50% Tolerance	100% Tolerance
1	Slack bus failed	Slack bus failed	Slack bus failed	Slack bus failed
2	Bus no. 2 failed 1→5 Slack bus failed	Bus no. 2 failed 1→5 Slack bus failed	Bus no. 2 failed 1→5 Slack bus failed	Bus no. 2 failed 1→5 Slack bus failed
3	Convergence not verified	Bus no. 3 failed	Bus no. 3 failed	Bus no. 3 failed
4	Convergence not verified	Convergence not verified	Convergence not verified	Bus no. 4 failed Bus no. 7 failed Bus no. 8 failed Bus no. 9 failed
5	Bus no. 5 failed Bus no. 6 failed Control Center failed	Bus no. 5 failed Bus no. 6 failed Control Center failed	Bus no. 5 failed Bus no. 6 failed Control Center failed	Bus no. 5 failed Bus no. 6 failed Control Center failed
6	Bus no. 10 failed	Bus no. 10 failed	Bus no. 10 failed	Bus no. 10 failed
7	Bus no. 11 failed 9→10 Bus no. 10 failed	Bus no. 11 failed 9→10 Bus no. 10 failed	Bus no. 11 failed 9→10 Bus no. 10 failed	Bus no. 11 failed 9→10 Bus no. 10 failed
8	Bus no. 12 failed	Bus no. 12 failed	Bus no. 12 failed	Bus no. 12 failed
9	Convergence not verified	Convergence not verified	Bus no. 13 failed 9→14 Bus no. 14 disabled	Bus no. 13 failed
10	Bus no. 14 failed	Bus no. 14 failed	Bus no. 14 failed	Bus no. 14 failed