Impact of Smart Grids on The Reliability of Distribution Systems

Impacto de las Redes Inteligentes en la Confiabilidad de los Sistemas de Distribución

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Abstract

Smart Grid conception spreads the idea about an efficient, safe and flexible electric system capable of monitoring the health of the grid, take fast actions to recovery it after a contingence and to integrate Distributed Generation near to the delivery points of energy. These characteristics aim to improve the performance of the network, to reduce the outages and the service restore time, and to give the opportunity to the customers to manage their own use of the energy.

Efficiency, reliability, cost reduction and the decrease of the CO2 emissions are the promises of the Smart Grids, in this context, this investigation aim to study the impact of different smart grid technologies in the reliability of the distributions systems.

Solutions like manual and automatic loops, distributed generation, automatic control systems, fault locators and automatic restore of the service are applied to a test radial distribution system, RBTS bus 2, with the purpose of compared their effect in the reliability indices of the system. Based on the series principle to calculate the reliability of radial systems, a software developed in Matlab is used to compare two base cases and eight test cases that apply smart techniques.

The results of the reliability case studies show that employing a convenient set of the smart grid technologies in radial power distribution system can practically diminish all the reliability indices. Furthermore, it is possible to reduce the range of variation of the reliability indices among different customers connected to the same feeder.

***Index terms*– Reliability, Smart Grids, Distribution Systems.**

Resumen

La concepción de Redes Inteligentes extiende la idea de un sistema eléctrico eficiente, seguro y flexible, capaz de monitorear la salud de la red, tomar acciones rápidas de recuperación después de una contingencia e integrar Generación Distribuida cerca de los puntos de entrega de energía. Esto conduce a una mejora del desempeño de la red, la reducción de las interrupciones y el tiempo de restauración del servicio, y dan la oportunidad a los clientes de gestionar su uso de la energía.

Eficiencia, confiabilidad, reducción de costos y reducción de las emisiones de CO2 son las promesas de las Redes inteligentes. En este contexto, esta investigación tiene por objetivo estudiar el impacto de diferentes tecnologías de redes inteligentes a la confiabilidad de los sistemas de distribución.

Soluciones como lazos manuales y automáticos, control automático, localizadores de fallas, generación distribuida y restauración automática del servicio, son aplicadas al sistema de pruebas RTBS bus 2, con el propósito de comparar sus efectos en los índices de confiabilidad del sistema. En base al principio de elementos en serie para calcular la confiabilidad de sistemas radiales, un software desarrollado en Matlab fue usado para comparar dos casos bases y ocho casos de prueba que aplican tecnologías inteligentes.

Los resultados muestran que usando una combinación de tecnologías de redes inteligentes en sistemas de distribución radiales, es posible reducir los índices de confiabilidad y que además, es posible reducir la diferencia entre los índices de confiabilidad entre los usuarios conectados en diferentes partes del alimentador radial.

***Palabras clave*– Confiabilidad, redes inteligentes, sistemas de distribución.**

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1. INTRODUCTION

The current life-style has increased the dependence on electricity service, it is vital to customers to receive energy with high reliability, quality and safety at an economic price.

Reliability is the probability of a device or system performing its function adequately, for the established period, under the intended operating conditions. Related to power systems, it is described by the number of outages during the year and the time to restore the services. Reliability is an important concern in the stages of planning, design and operation of power systems, because of the fact it represents a measurement of the satisfaction of the final customer and could help to identify the weakest points of the grid, which need bigger investments.

The topic takes special importance in radial distribution systems, where any fault could affect all the customers in the feeder. This has caused that electric power distribution systems become the main contributors to customer reliability problems [1].

Many studies have been developed the last years to improve the reliability of radial systems, all of them aim to the implementation of solutions related to Smart Grids, which stands out the utilization of intelligent device and improved communication networks [2]. Smart technology permits to monitor and to manage in real time [3] the delivery of energy to the end-users, enabling the automation and self-healing of the network, the integration of distributed energy sources, and the active participation of the customers.

This project focuses on the incorporation of smart technology to the distribution system and their impact on the reliability of the system.

A detailed study of this subject will be undertaken, focus on the advantages of ACRs, fault locators, feeder automation and the implementation of distributed generation against classical distribution systems. Which are exposed in seven study cases.

All the cases evaluated with smart technology show that smart technology could improve the reliability of the radial systems, although the percentage of improvement differs between the cases.

The structure of the article is divided in five parts. The first one gives a basic introduction to reliability concepts, index and calculation methods. Smart grid definition, advantages and its impact on electric networks are discussed in the second part. The third part presents the design and operational philosophies for each case of study to get a quantitative comparison of the reliability indices. The design of the software and the results are summarized in the fourth part. Finally, conclusions and recommendations for further studies are presented.

2. RELIABILITY CONCEPTS

The function of an electric power system is to satisfy the system load requirements as economically as possible and with a reasonable assurance of continuity and quality. In [5] the reliability of a power system is described like the ability of the system to provide an adequate supply of electrical energy. This concept includes two basic aspects of the system:

- Adequacy: it is associated to the static conditions of the system and is described as the existence of sufficient facilities to satisfy the costumer load demand (generation, transmission and distribution facilities)

- Security: is the ability of the system to recovery when disturbances occur in the network. This condition includes the disturbance associated with local and widespread disturbance such as the loss of generation or transmission facilities.

Rarely the distribution systems are loaded near their limits, hence the studies of reliability emphasize on the security of the system and are mainly focused on customer interruptions and equipment outage. Many utilities in the world use reliability analysis results to track their performance and the customer satisfaction. Moreover, the regulators of the energy markets are beginning to penalize the performance of utilities based on the reliability indices as well as to compensate customers for long interruptions.

2.1. Reliability Indices

According to [6] and [7], the reliability analysis considers two types of indices:

2.1.1 Load oriented indices

Are defined for each load point (i) and are calculated considering the frequency and duration of the states when the load point is not supplied:

- Failure rate (λ): average of times that an element is subject to a failure involving the operation of a protection device.

- Repair Time (r): it includes the time to locate the failure, clearance time and restore time.

- Annual average outage time: U

- Expectation of unserved energy: E

2.1.2 System indices

Defined for the whole electrical network, representing the overall system reliability for the customers.

- SAIFI: System Average Interruption Frequency Index:

$$SAIFI = \frac{\sum Total\ number\ of\ customer\ interrupted}{Total\ number\ of\ customer\ served} \qquad (1)$$

- SAIDI - System Average Interruption Duration Index:

$$SAIDI = \frac{\sum \text{Customer minutes of interruptions}}{\text{Total number of customer served}} \qquad (2)$$

- CAIDI - Customer Average Interruption Duration Index:

$$\text{CAIDI} = \frac{\sum \text{Customer minutes of interruptions}}{\sum \text{Total number of customer interrupted}} \qquad (3)$$

- ASAI - Average Service Availability Index

$$ASAI = \frac{Customer\ hours\ of\ available\ service}{customer\ hours\ demanded} \qquad (3)$$

- ENS - Energy not supplied

$$ENS = \sum_{i}^{N_T} L_{a(i)} U_i \qquad (4)$$

In the basis of these indices, relative reliability analysis could be development by evaluating the behavior of the system before and after a change in the design or the operation conditions.

2.2. Reliability Analysis Methods

There are different approaches to get a quantitative analysis of the reliability of a distribution systems. The most important are described below.

2.2.1 Analytical methods

Used to evaluate the mean or expected values of the load point and system reliability indices [8]. They are based on the representation of the system by a mathematical model and use numerical solutions to evaluate the reliability. These types of methods do not consider the random behavior of the system.

- **Markov Chain Model:** It consists of a list of the possible states of a system, the possible transition paths between those states, and the rate parameters of those transitions. In reliability analysis, the transitions usually consist of failures and repairs [9].

In base on stationary Markov process, the duration-frequency technique could be used to evaluate the reliability of radial distribution systems when the failure frequency (λ) and repair time (r) are considering as constant, in which case the probability of transition between two states (normal operation and failure) remain constant over the time, as it is showed in the Fig.1.

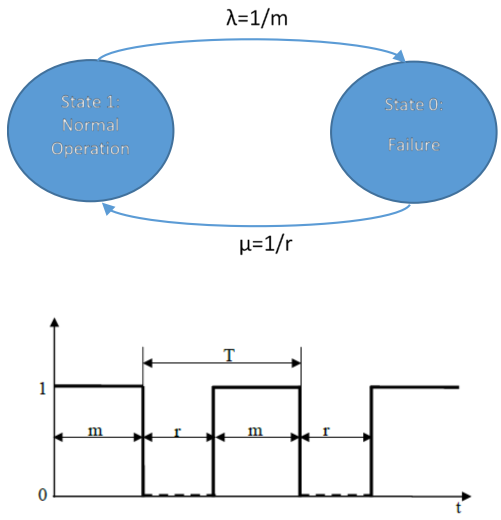

Figure 1: States Cycle of a Component

- **Failure mode and effects analysis or Minimal Cut-set:** A cut-set is a set of components whose failure alone will cause system failure. A minimal cut-set is the unique combination of component failures that can cause system failure [10].

A radial distribution system, showed in the Fig. 2, is a set of series components, where a customer connected λ to a load point requires that all the components between himself and the supply are operating. Based on the series system principle [1], the three basic parameters: the average failure rate (λs), outage time (rs), and average annual outage time (Us) are given by the equations 6-8.

$$\lambda s = \sum_{i=1}^{n}(\lambda i) \qquad (5)$$

$$Us = \sum_{i=1}^{n}(\lambda i * ri) \qquad (6)$$

$$rs = \frac{Us}{\lambda s} \qquad (7)$$

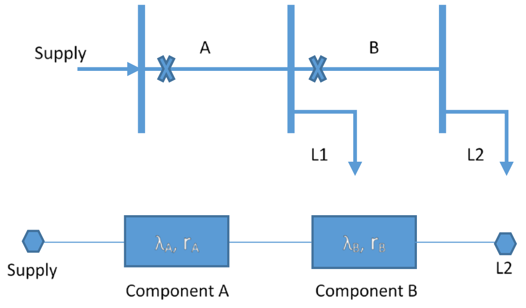

Figure 2: Minimal Cut Sets for Load 2 – Series System Principle

2.2.2 Stochastic Simulation Methods – Monte Carlo Simulation

The Monte Carlo method is based on the repetitive generation of random events and counting the occurrence number of specific condition. The random events represent the values of the variables in the system, and with them it is possible to create an artificial history of the system [11]. This approach is useful to examine and predict the behavior of the system, to get the probability distributions of the reliability parameters of the loads and to estimate their average values [8].

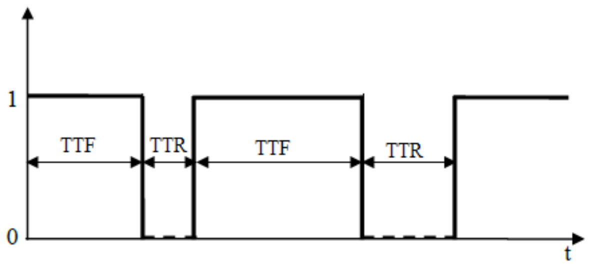

Figure 3: Element Operating/Repair History [8]

Based on this history and the analysis of the loads affected by each component of the network, it is possible to get expected values for the loads and system reliability indices.

3. SMART GRIDS

The International Energy Agency defined the smart grid as an "electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability" [12]. Fig.4 shows the roadmap of the Smart Grids.

The main characteristics of a Smart Grid technology, defined in [13-14], are:

- Increased use of control and protection digital devices, and the application of information technologies with real time availability.
- Inclusion of demand side response (DSR) technologies, demand side management (DSM) technologies, and energy efficiency solutions.
- Integration of renewal distributed generation (RDG) and energy storage.
- Deployment of smart devices for metering, communications, operations and status, and distribution automation.
- Incorporation of smart appliances and consumer devices that provide control options and timely information.
- Dynamic optimization of grid resources.

The key factors for asses the evolution of the grids and for measuring the progress and benefits are defined in [15-17] as:

- Reliability: reduction of time/frequency of interruptions and power quality disturbances. The grid takes corrective action when it is required.
- Security: diminution of the probability and consequences of manmade attacks and natural disasters.
- Cost: guarantee fair prices of electricity and suitable supplies.
- Efficiency: reduction of the cost to produce, deliver, and consume electricity
- Environmental: enable a larger penetration of renewable sources, which decrease CO2 emissions.
- Safety: minimize the injuries and loss of life from grid-related events.

For each stage of power systems, there are specific Smart Grid technologies that help to improve one of the key assessment factors, and are part of the above key areas. The aim of this paper is limited to the developed technology that can be used in distribution systems.

3.1. Smart Grid Technologies for Distribution Systems

Today, customers are the first to notify about disruptions of service to the utilities. When it happens, crews are dispatched to diagnose the problem, manually restore power to the healthy parts of the

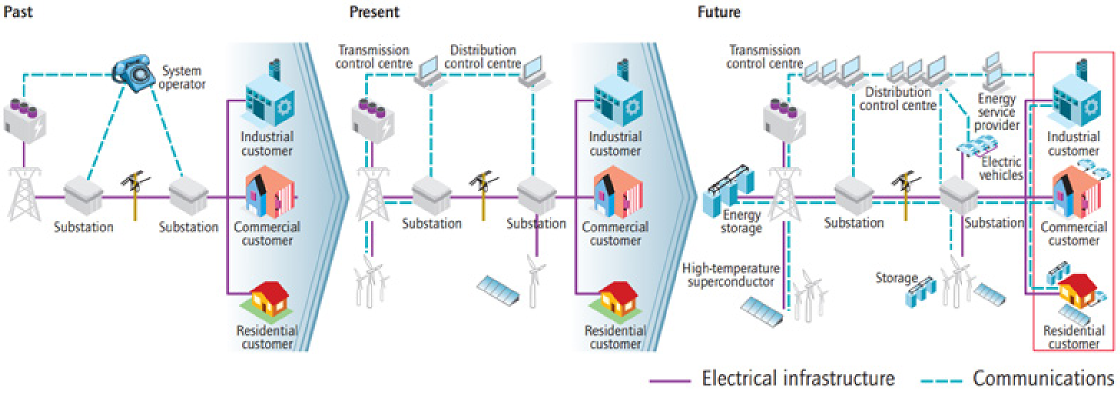

Figure 4: Smart Electricity Systems [12]

system and execute the repair of the affected areas.

This procedure takes a long time and exposes the personnel, who should work near of energized equipment. This can be avoided, using sensor along feeders, automatic reclosers for system reconfiguration, distribution automation that enable self-healing capabilities, and the introduction of concepts like Fault Detection, Isolation and Restoration (FDIR) [18], which also allow the reduction of the recovery times of the system after a contingency.

On the other hand, the integration of distributed energy sources (DG) like wind farms, photovoltaic, internal combustion engines and fuel cells as well as energy storage systems, have economic and environmental benefits and serve to make the distribution system more flexible [19] and to reduce the number and frequency of the outages.

Previous research had performed analysis of the impact of reliability on distribution systems. Sagar and Prasad [20] compared the reliability indices of a radial system, Haughton and Weydt [21] studied automatic reconfiguration to improve reliability. Kazemi [22] propose the design of an automatic loop restoration scheme. Abdulwahab [23] study the impact of ground fault protection (GFN) in network form a reliability point of view and Mancasi and Vatu [24], use Monte Carlo method to evaluate Smart Grids Reliability. These researches are the basis of this investigation.

4. Proposed Analysis

4.1. Test System

To evaluate the impact on the reliability of the different Smart Grids technologies, a Roy Billinton Test System (RBTS) Bus 2 was chosen [25]. This system has four feeders (F1 - F4), which are operated as radial feeders, but connected as a mesh through normally open sectionalizing points. The single line diagram of Bus 2 is displayed in the Fig.5.

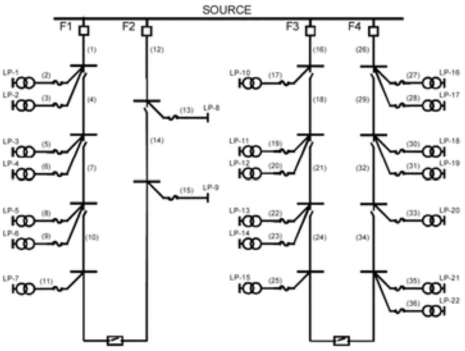

Figure 5: RBTS – Bus 2

The selectión of this test system were based on:

- It represents a combination of different types of loads: residential, commercial, small users and government/institutional.
- Enough switching elements and nodes are part of the system to test smart grids technologies.
- Feeder interconnections are possible by open-tie switches.
- It is simple enough to add elements and to be analyzed by simulations.

4.2. Cases of Study:

Eight study cases have been selected for the analysis. In the Table 1, the study cases, their characteristics and the operation philosophy are described in detail.

4.3. Computational Program

4.3.1 Design and network structure

To develop the simulations, a program was written in Matlab to calculate the basic reliability indices for each load and the system reliability indices, according to:

- The analytical approach for reliability analysis based on Markov series.

- The principle of first order cut sets (series components), considering that in the radial systems a customer connected to a load point requires that all the components between himself and the supply are operating.

- The general and specific operational conditions described in table 1 for each case.

4.3.2 *Inputs – Database*

The input of the program is a kind of database development in Excel with three main tables:

- Load table

NODE	FEEDER	TYPE	AVERAGE	PEAK	CUSTOMERS

Figure 6: Information of Load Table

Type: 1.Residential 2. Small user 3. Gov./Inst. 4.Commercial

- Branch table

FROM	TO	TYPE	PROTECTION DEVICE	SMART DEVICE	FAULT RATE (λ)	LENGTH	REPAIR TIME	MAIN FEEDER

Figure 7: Information of Load Table

Type: 1. Main branch 2. Lateral branch 3. Transformer

Protection Device: 1.CB 2.Disconector 3.Fuses 4.Not apply

Smart Device: 0.Not available 1.Fault locator 2. FDIR

Fault Rate: average fault rate of the component

- Source table

FROM	TO	TYPE 1	TYPE 2

Figure 8: Information of Source Table

Type 1: 1. Loop 0. RDG

Type 2: depends on the value of Type 1. For loop specify the type of the switching device 1. Disconnector 2. Recloser. For RGD specify the type of generator 1. Island 2. Grid/island

4.3.4 *The algorithm*

For each load of the system, the program analyses how the branch's failures in the same feeder affect the load reliability, based on the following conditions:

- The location of the load in relation to the point of failure: upstream or downstream.

- The type of branch: main, lateral or transformer.

- The type of device used for the isolation/ sectioning: Circuit breaker/recloser, disconnector, fuse, or without protection.

- The availability of smart technology.

- The availability of alternative sources.

Fig. 9 and 10 display the flow chart that illustrated the logic process.

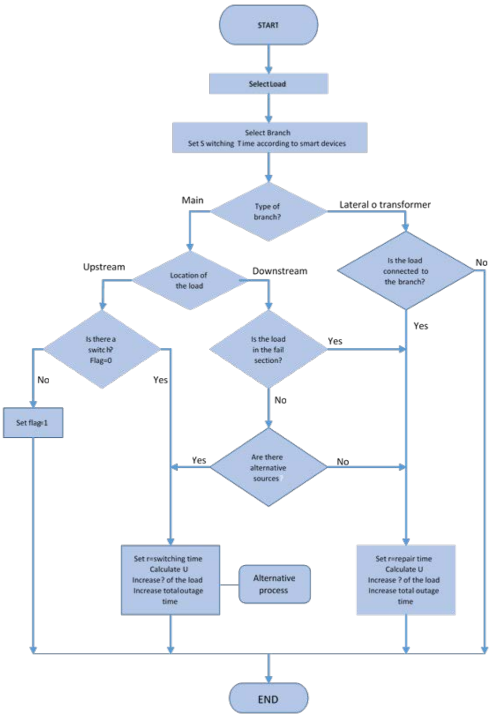

Figure 9: Flowchart of the Basic Process

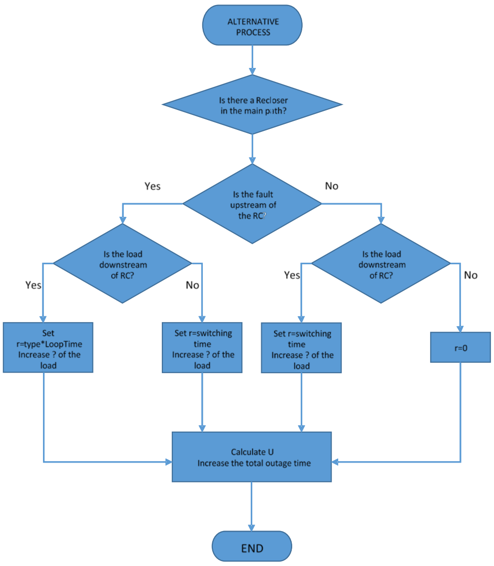

Figure 10: Flowchart of the Logic with Advance Smart Technologic and Alternative Sources

Table 1: Description of the Study Cases

Case	Description	Switching devices	Smart Technology	Alternative sources	Philosophy of operation:	Switching time
Base Case 1	Traditional Distribution System	manual switches in the main branches and fuses in lateral branches.	-	-	Crews available to look for and locate the faulted section, perform manual local switching and repair the affected branch.	1 hour
Base Case 2	Fault detection isolation and restoration (FDIR)	manual switches in the main branches and fuses in lateral branches.	-	Feeder interconection	Crews available to look for and locate the faulted section, perform manual local switching and repair the affected branch.	1 hour
Case 1	Fault Location scheme	switches in the main branches and fuses in lateral branches.	fault locators, RTU, SCADA/DMS		Fault locators provide information related to the branch where there is a short circuit, to the operator of the control centre. The operator can perform remote switching with the SCADA to restore power to the healthy section.	10 minutes
Case 2	Fault detection isolation and restoration (FDIR)	switches in the main branches and fuses in lateral branches	FDIR, RTU, SCADA/DMS		Automatic scheme that provides fault detection and location, fault isolation and power restoration to the healthy part of the system without human intervention	1 min
Case 3	Basic automation scheme – normally close circuit breakers at midline with fault detection and isolation capabilities	circuit breakers in the midline of the feeder, switches in the other main branches and fuses in lateral branches.			Automatic isolation of the fault is performed by the circuit breaker. Thus, the branches upstream of the circuit breaker are not affected by the fault. Manual and local operation of the switches	1 hour
Case 4	Basic automation scheme – normally close circuit breaker in each section of the main feeder with fault detections and isolation capabilities	circuit breakers in the main branches and fuses in lateral branches			Automatic isolation of the fault is performed by the circuit breakers, thus the branches upstream of the circuit breaker are not affected by the fault.	1 hour
Case 5	Renewal Distributed Generation (RDG)	switches in the main branches, fuses in lateral branches and CB for the generator.		Generators connect at the end of each feeder	Generator that forma an island in the system and provide energy to the load point located downstream of the fault in the healthy sections of the feeder. Manual switching for isolation/restore actions	1 hour
Case 6	Loop with Automatic Circuit Reclosers (ACR)	NC reclosers are installed in midline between 2 feeder and a NO tie-recloser that allows a loop between the two feeders	Each recloser is equipped with a local automatic control system (ACS), without communication link between them, which operate in accordance with pre-defined instructions. Each ACS has sensors to detect loss of voltage, timers and relays for automatic operation	feeder interconnections	Automatic restoration based on delays preconfigured in each unit. Faults Upstream of RC1, RC2: - RC1 and RC2 open automatically after a delay when detect loss of voltage - RC3 close automatically after a delay when detects loss of voltage. - The delays in RC1 y RC2 are less than the delay set in RC3 to avoid the propagation of the fault to the other feeder. - The time required for the restoration of the healthy area is defined as Loop Time. - The switches and circuit breakers are opened/closed manually, after the fault is located to restore the service to the healthy part. Faults Downstream of RC1, RC2: - RC1 and RC2 open to isolate the faults. Load points upstream are not affected. - Switches and reclosers are opened/closed manually, after the fault is located to restore the service to the healthy part.	1 hour.
Case 7	Renewal Distributed Generation with ACS and fast electronic circuit breakers	- NC reclosers installed in midline of the feeders, - NC electronic circuit breakers for the connexion of the generators when they operate with the grid - NO electronic circuit breakers for the connexion of the generators when they operate as an island.	- Reclosers and circuit breakers are equipped with an ACS and communication link between them in order to operate coordinately. - Each ACS has sensors to detect loss of voltage, timers and relays for automatic operation. - Electronic switches commutate faster enough to do not produce disconnection of the load points.	Renewal generators connected at the end of the feeders. RDG normally operate connected to the grid and in case of failure of the main source operate as islands.	Faults Upstream of the reclosers: - The reclosers open automatically when detect loss of voltage. - Main CBs and disconnectors are closed manually by the operator, after the fault is located. Faults Downstream of the reclosers: - The reclosers open to isolate the faults. Load points upstream are not affected. - Switches, reclosers and CB are opened/closed manually, after the fault is located to restore the service to the healthy part.	1 hour
Case 8	Integration of the solutions applied in cases 2 and 7	- NC reclosers installed in midline of the feeders, - NC electronic circuit breakers for the connexion of the generators when they operate with the grid, - NO electronic circuit breakers for the connexion of the generators when they operate as an island.	FDIR, RTU, SCADA/DMS, ACS	renewal generators connected at the end of the feeders and integrated to the grid		1 minute.

4.4. Results and Analysis

The results of the simulations for the eight cases are presented in this section. The analysis of the results includes the changes in the reliability based on differences with the base case one (BC1) for the load oriented indices and with the two base cases for the customer oriented indices.

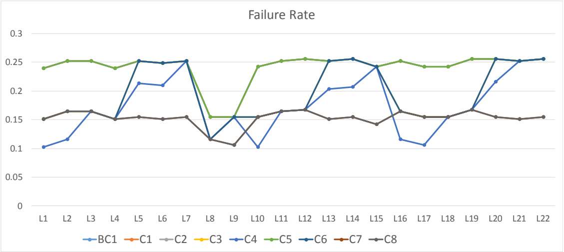

Figure 11: Failure Rate for all the Cases

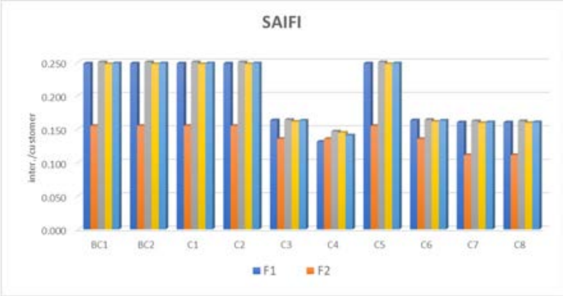

Figure 12: SAIFI Values for all the Cases

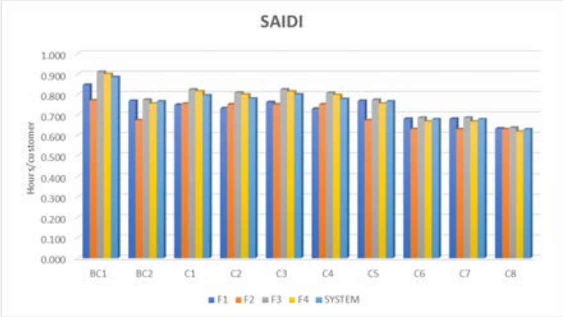

Figure 13: SAIDI Values for all the Cases

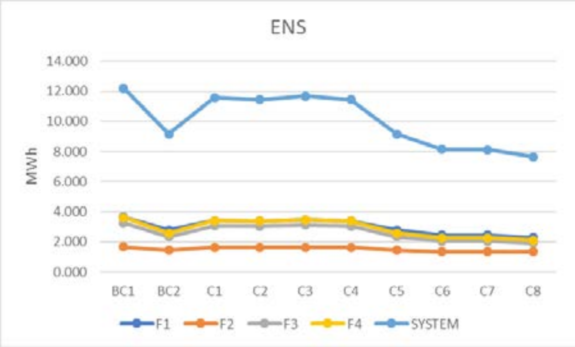

Figure 14: ENS Values for all the Cases

The analysis of the results shows:

- The reduction of failure rate and SAIFI is more related to the employment of automated distribution systems: circuit breakers, automatic reclosers, ACS as well as alternative sources with automatic capabilities.

- The decrease of SAIDI and the outage duration is associated with the use of smart technologies for the location and isolation of the faults, and the implementation of alternative sources.

- Fault locators and FDIR reduce the duration of the outages for the customer that can be isolated from the failed section, by improving the procedures to address faults and to restore the service.

- Automatic reclosers and circuit breakers provide selectivity of the areas that should be disconnected in case of fault. This reduces the number of customers affected by permanent faults and hence, the number of faults sensing by a customer.

- Distributed generation suitable to work integrated to the grid mainly improve the indices of the loads connected at the end of the feeder, which reliability usually is poor.

- Distribution systems with ring configuration have minor outage times and SAIDI, however the frequency of the interruptions and SAIDI only improve if smart technology is applied to this topology.

- The selection of location of the automatic reclosers in the solution with intelligent systems, depends of the loads whose indices should be improved.

- The results show that the use of multiple smart grid techniques -Case 8- has a cumulative effect on reliability improvement.

5. CONCLUSIONS AND RECOMENDATIONS

- It is most difficult to improve the reliability index of the loads connected at the end of the feeder. The best way is the implementation of DG with automatic control and normally connected to the grid.

- Although the improvement is not extraordinary, the availability of the system increases with the intelligence and autonomy that it has.

- Although BC2 shows better results related to ENS that the cases with fault locators and feeder automatization, should be considered that this analysis assumes transfers withot restrictions.

- The analysis demonstrated that the benefits from the solutions presented are additive, therefore modern distribution systems should tend to implement more that one of these solutions.

- The use of distributed generation in the grid help to avoid the outage by reducing the duration of the failures. Also, DG can contribute to grid connected power demand reduction, which imposes less stresses on substation equipment and grid components, resulting in the indirect benefit of decreased component failure rates.

- Evidently, it is not possible to avoid and mitigate all interruptions, but the adoption of smart technologies plus a good planning can decrease the rate of occurrence of service interruptions.

- More complex analysis could be made that consider temporary interruptions and the failure of switches, control breakers, protection and control systems.

- All the analysis can be more accurate and real if the failure rate of equipment is based on aging, maintenance schedule, whether and other parameters related to the failure rate.

- All the results can be improved if instead of the use average values for the frequency of interruptions and repair time for the elements like in Marvo chain model, the random nature of these variable is contemplated by the application of probabilistic methods like Monte Carlo Simulations to build the history of the system.

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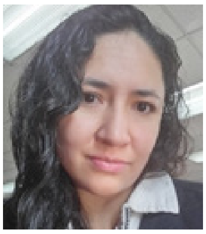

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