MORE MICROGRIDS – Advanced Architectures and Control Concepts for More Microgrids

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1. Introduction

In recent years, electric power systems have changed their structure by increasing the competition in order to achieve better performance and efficiency in the electricity production, transmission and distribution [1, 2]. One of the most important aspects of the competitive electric energy market is the operation of independent power producers that can be connected at any system voltage level. This fact together with the additional financial incentives being applied in many countries worldwide has increased considerably the number of power generating units using renewable energy sources and more advanced technologies. This new environment concerns distributed generation where the customers own their generating units becoming both producers and consumers of electricity [3, 4].

Distributed generation sources are adopting advanced technologies of electric power generation and have introduced significant changes in the structure of the systems to which they are connected. It is evident that the reliability performance of these power systems is seriously affected by the operation of the distributed generating units. Therefore, improved computational methods must be developed which can model the additional operating features of the systems. The system reliability performance is mainly quantified by calculating appropriate reliability indices which must take into account all the system features. For this purpose, the improved methods must calculate an extended set of reliability and operational indices for each system under study in order to quantify the effect of each system parameter on the system reliability performance.

The present report is concentrated in power distribution systems that are the area of application for microgrids. Its major objective is to assess the impact of distributed generation on the reliability performance of power distribution systems which operate applying the principles of competitive electric energy market. It is assumed that these systems are connected to power transmission systems through appropriate substations while additional power generating units can be connected to their nodes. These units mainly use renewable energy sources (photovoltaic and wind generating units) and a broad range of new technologies, such as fuel cells and microturbines. Another very important system feature that is taken into account is the operation of distributed generation in parallel with the high-voltage transmission supply system and its performance during abnormal conditions such as power supply outages. In addition, it is assumed that normally open switches may exist in the distribution networks connecting adjoining distribution feeders. They may be energised through loop power flow controllers in order to provide alternative routes of power flow in the relevant feeders when it is required due to failures of the distribution network components.

An improved and efficient computational methodology was developed for calculating the reliability and operational indices of distribution systems incorporating distributed generation [4]. The Monte-Carlo sequential simulation approach is used for simulating the system operation while appropriate models were developed and incorporated into the developed methodology for modelling the particular features of distributed generating units and system customer categories.

This report presents the characteristics of an extended computational methodology that was developed for quantifying the impact of the failures on distribution system components and the operation of normally open switches. Furthermore, the report includes the analysis being conducted for a typical low voltage distribution network with multiple feeders supplying different categories of customers (industrial, commercial and residential) in alternative system planning schemes. These schemes include the operation of normally open switches through loop power flow controllers while various technical and operational features of these switches are also considered.

2. Main Features of Distribution Systems and Distributed Generation Sources

The reliability assessment of power distribution systems requires appropriate modelling of their features which affect their operation and, especially, the features of distributed generation. The most important issues that require a further investigation is the system topology, the customers' profiles and operational characteristics of the distributed generation sources.

In a generic representation of a distribution system with distributed generation, one or more feeders are connected to a MV/LV substation, which is the normal supply source of the system load demand. Each feeder has a radial topology and power is supplied by the electric utility through the MV/LV substation. Under normal conditions, the system supply source is capable of supplying a certain percentage of the total load demand of system customers (70%-100% of peak load demand) due to existing limitations of the MV/LV substation. The system supply source is considered to have an operating cost function (in Eurocent/kWh), which is assumed to vary in each hour of the day, and this variation mainly depends on the particular supply and load demand requirements of the system (competitive electrical energy market).

Furthermore, it can be considered that normally open switches using loop power flow controllers may exist in the distribution network that can connect the adjoining feeders [5]. Therefore, the system reliability performance will be significantly improved since alternative routes of power supply will be provided in order to prevent the occurrence of load interruptions or minimise their impact in cases of power supply disturbances due to the outages of distribution network components. It is also known that the closed loop feeders have certain advantages when they are compared with the radial feeders. These advantages mostly concern the decrease of power losses and the improvement of the voltage profile, especially when there is a considerable unbalance loading among the feeders, while the flexibility to cope with the load growth is also of great importance. However, besides the increased complexity of the protection scheme of the feeders, the closed loop operation has additional disadvantages concerning the increase of the short circuit currents and the frequency and severity of the voltage dip.

The nodes of the distribution network can either be simple nodes or customer nodes. Each customer node supplies customers of certain categories, which can be industrial, commercial, agricultural and residential customers. Table 1 presents the major areas of activities for each of these four categories of customers. The system load demand requirements are determined by the peak load demand of each system customer node and its customer categories and the annual chronological load demand curve of each customer category (8760 points). Figures 1, 2 and 3 present typical daily load demand curves of residential, commercial and industrial of customers.

Table 1: Major areas of activities for customer categories

Industrial	***Commercial***	***Agricultural***
Mining	Construction, Wholesale	Organisations in Irrigation Activities
Textile	Commercial Shops	Drainage Activities
Metal Fabrication	Hotels, Restaurants, Bars, etc.,	Cultivation Activities
Non Metal Fabrication	Organisations in Transportation, Communications, Information, Research	Cattle Breeding Activities
Food	Civil Services, Hospitals, Banks, etc.,	
Chemical		

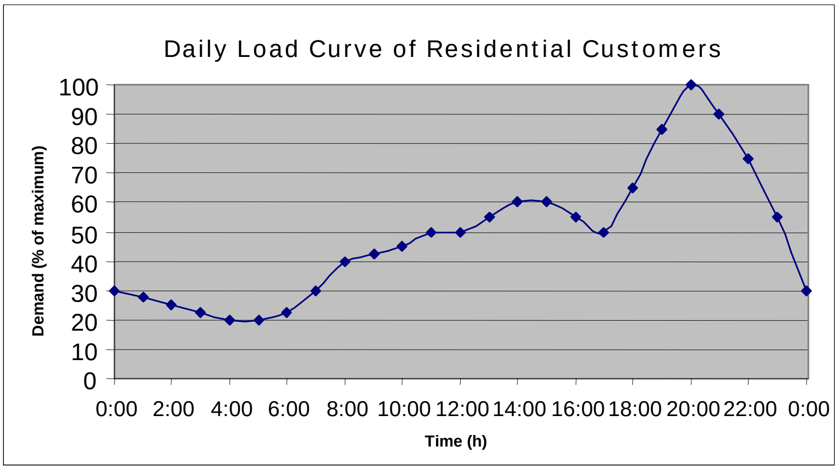

Figure 1: Daily load demand curve of residential customers

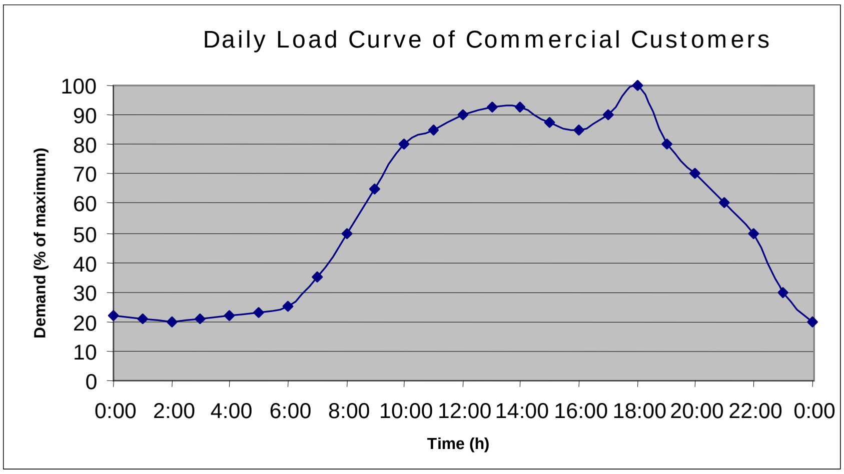

Figure 2: Daily load demand curve of commercial customers

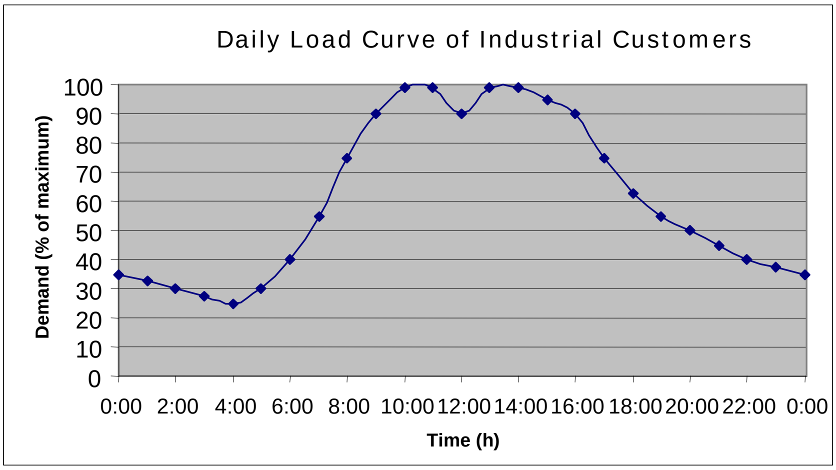

Figure 3: Daily load demand curve of industrial customers

In the modern competitive electric energy market, various distributed generation sources may exist with different technological and operational characteristics. They can be located anywhere within the distribution system and they are connected either to a simple node or a customer node. Distributed generation covers a broad range of technologies, including many renewable energy technologies supplying small-scale power at sites close to users. Highly efficient combined heat and power (CHP) plants, back-up and peak load systems are providing increasing capacity. The present reliability assessment study considers four different technologies (wind generating units, microturbines, fuel cells and photovoltaics) and their impact on the power distribution reliability performance is calculated.

Wind generating units are based on wind turbines and several units can be installed at one site to build a wind farm of the desired power production capacity. The main push has been in large wind farms where wind turbines from 700kW to 1.5MW are available and in use. Several smaller wind turbines (<250kW) are available for use in Microgrids. When the wind turbine is operating in a stand-alone mode, any power requirement in excess of the produced power must be supplied by storage systems or other types of generation. Because they commonly use induction generators, small wind turbines are not easily adapted to Microgrid operation unless other sources supply voltage and frequency control.

Microturbines are composed of a generator and small gas turbine mounted on a single shaft. Most microturbines are fueled by natural gas but they can also use liquid fuels such as diesel or jet fuel. These units currently range in sizes from 30 to about 100kW, while larger units are under development. Most microturbines also have a recuperator to recycle some exhaust heat back to the combustor. Because the combustion process is closely controlled and relies on relatively clean burning fuels, microturbines typically produce few emissions.

Fuel cells constitute an attractive power generation technology because of their potential for highly effective conversion to electrical power (35 to 55 percent without heat recovery). The only technology in general use today is the phosphoric acid fuel cell, which is available in the 200kW size range. A number of other fuel cell technologies are being developed and they operate in a similar manner electrically although they differ in other features. The ability of a fuel cell to change load levels is dictated by its ability to produce more voltage through consumption of additional fuel.

Photovoltaics (PV) rely on sunlight to produce DC voltage at cell terminals and their power production depends on the intensity of sunlight and the design of the cell. PV systems use cell arrays that are either fixed or track the sun to capture additional energy. Photovoltaics, like microturbines and fuel cells, generate DC voltage that must pass through an inverter to produce 50-Hz alternating current for distribution on the utility grid. The capability of PV systems to follow load changes is limited by the available sunlight. Therefore, energy storage systems are required for stand - alone systems if additional power is required.

Electric energy storage systems (ESS) can be connected at any busbar of the power distribution network and their basic configuration mainly consists of an energy storage element (battery) and a converter (DC/AC). Two main modes of operation are recognised that are the charging and the discharging modes. Each ESS is characterised by the following parameters:

- maximum energy storage C_{max} (in MWh)
- minimum energy storage C_{min} (in MWh)
- maximum power for discharge P_c (in MW) which is usually determined as the rating of the relevant converter
- coefficient a ($0<a<1$) that integrates all the efficiency parameters of the ESS components and represents the combined efficiency of ESS that is taken into account for determining the maximum power for charging (aP_c)

- discharging coefficient w (0<w<1) that determines the end of a discharging mode of operation (energy storage level C lying between w C_{max} and C_{min}) and the starting of a charging mode of operation
- charging coefficient k (0<k<1) that determines the end of a charging mode of operation (energy storage level C lying between k C_{max} and C_{max}).

The electric energy storage systems (ESS) can be used in the following distinct types of applications:

1. System regulation: They can provide power to meet short term random fluctuations in load demand in order to avoid the need for frequency regulation by the system generating units. They can also provide ride through for momentary power outages, reduce harmonic distortions and eliminate voltage sags and surges. It can be considered that this type of applications is an issue being described in the power quality assessment of power supply systems.
2. Spinning reserve: They can provide power in order to eliminate the need for keeping one or more generating units in low load conditions (healthy state) or to increase the existing not adequate level (marginal state) so that the deterministic security criterion N – 1 is satisfied (well-being framework for the reliability analysis).
3. Supply of load demand to be curtailed: They can provide power in order to avoid or reduce the need for load curtailment during the failure events where the available system generating capacity from all other sources can not supply the respective total load demand (risk state of the well-being framework for the reliability analysis).
4. Peak shaving: They can provide power during the time periods of the daily system operation where peak load demands occur. This will avoid the operation of generating units with a high production cost.
5. Load levelling: They can provide storage of surplus electric energy being generated during off-peak time periods of the day (i.e. overnight) in order to supply the increased load demand during the other time periods. This type of application can be combined with the excessive usage of renewable energy sources that show a fluctuating generation capacity output.

The above different types of applications for electric energy storage systems can provide strategic advantages (fuel flexibility, generation technology), production cost savings and decreased environmental impact (integration of renewable sources). However, their most important advantage concerns the improved reliability performance of the power supply system either for the power quality issues or for the continuity of load supply. Since the reliability assessment being described in this report is not concerned with power quality issues, the above type 1 of applications is not considered.

The technology of chemical energy storage using batteries is considered for ESS since it has received wide attention in many practical applications worldwide. There are five main classes of battery (lead acid, alkaline, regenerative fuel cell, high temperature and lithium) that are manufactured while significant research effort is shown for using better materials, improving their technical characteristics, lowering their cost figures and increasing their reliability performance parameters. Each class of battery has its own advantages and disadvantages that must be taken into account when they are intended to be used in each type of applications and according to the features of the respective power supply system.

By taking into account the above described main characteristics of the distributed generation sources, it can be assumed that they have the following main operating features which depend on their specific technical characteristics:

- Maximum and Minimum Capacity (in kW).
- Start Up Time (zero or certain minutes).
- Operating Cost Function (in Euro): $Ax^2 + Bx + C$ where x is the energy being produced during the time period of one hour and A, B, C are appropriate parameters.
- Start Up Cost (in Euro).

Under normal system operating conditions, it is assumed that distributed generation sources can operate in the relevant time periods according to their specific technical characteristics:

- ❑ Wind turbines operate when the respective wind speed of the geographical location at which they are installed is greater than their respective wind speed characteristics while they also determine their power output.
- ❑ Photovoltaics operate when there is solar radiation while their technical characteristics and the characteristics of the geographical location at which they are installed determine their power output.
- ❑ Microturbines and fuel cells operate when their operating cost is lower than the respective operating cost of the system supply source.

Under system emergency conditions, when the system sources being in operation (normal system supply source, distributed generation sources) can not supply the respective system load demand, microturbines and fuel cells may be called on to operate according to their increased operating cost in order to supply the additional system load demand which can not be supplied.

The above dispatch procedure of generating units is applied when the failure events occuring on the distribution network components are ignored or their occurrence has no significant impact on the system operating performance. However, the failure events may create new subsystems within the entire system due to the isolation of certain network branches. The load demand of the subsystems that are not connected to the system supply source can be supplied by the power output of distributed generation sources that are located in the respective subsystems and can be called on to operate. If additional power is required in order to satisfy the load demand of certain subsystems, appropriate normally open switches can be energised through loop power flow controllers so that they can provide alternative routes of power flow to these subsystems and, therefore, their load demand is prevented to be curtailed.

All the above described design and operational features of distribution systems and distributed generating sources have been modelled appropriately and the respective models and the computational algorithm have been incorporated in an effective methodology that simulates realistically the system operation. The main purpose of the methodology is to calculate a set of appropriate indices that quantify the reliability and operational performance of these systems. For this purpose, appropriate deterministic security criteria have also been incorporated in order to assess the well-being of power distribution systems. The most commonly used deterministic security criterion (N – 1) is quantified by an appropriate generating capacity level that is equal to the power output of the generating unit which has the maximum value from all the generating units being in operation.

The sufficient system generation margin is provided by considering the spinning reserve margins of all the generating units being in operation (difference of their maximum output capacity and actual output level). All the system generating units (actual or equivalent ones) are considered. Therefore, for a particular time period, the index of the available system spinning reserve is calculated by assuming that there is a loss of the unit with the greatest value of actual output and adding the reserve margins of all the other units being in operation. The system is in its healthy state if the numerical value of this index is not smaller than the value of the capacity level quantifying the security criterion N – 1. It is evident that the satisfaction of the security criterion and the residence of the system in its healthy state may require the operation of additional generating units compared with the ones being required only for the supply of the respective system load demand. This means that these units must start operating while their technical characteristics (minimum power output) need to be considered appropriately. Another deterministic criterion widely used is a certain percentage of the respective total system load demand. In all cases, if the deterministic security criterion is satisfied, it is considered that the system resides in the healthy state. Otherwise, it is considered that the system resides in the marginal state of the well-being framework for the reliability analysis.

3. Monte-Carlo Sequential Simulation Method

The Monte–Carlo sequential simulation approach is a stochastic simulation procedure and can be used for calculating the operational and reliability indices of a power system by simulating its actual behaviour [6 – 8]. The problem is treated as a series of real experiments conducted in simulated time steps of one hour, which is considered adequate for a power system reliability analysis since the number of system changes within that time period is generally small. A series of system scenarios is obtained by hourly random drawings on the status of each system component and determining the hourly load demand. The operational and reliability indices are calculated for each hour with the process repeated for the remaining hours in the year (8760 hours). The annual reliability indices are calculated from the year's accumulation of data generated by the simulation process. The year continues to be simulated with new sets of random events until obtaining statistical convergence of the indices. The sequential simulation approach steps through time chronologically, by recognising that the status of a system component is not independent of its status in adjacent hours. Any event occurring within a particular time step is considered to occur at the end of the time step and the system state and statistical counters are updated accordingly. This approach can model any issues of concern that involve time correlations and can be used to calculate frequency and duration reliability indices. One very important advantage of the sequential simulation is the simplification of a particular system state simulation by considering information obtained from the analysis of the previous system states. This can only be applied when the system states change very little from one time step to the next. Such an assumption can be made for the power transmission and distribution systems that do not suffer large changes very often.

A computational method has been developed at NTUA for the reliability assessment of power systems applying the above principles of the Monte - Carlo sequential simulation approach [8]. This method is used as the basic method for developing the improved and efficient methodology being described in this report. The following main features were incorporated in the improved methodology:

1) The pseudo-random numbers are generated applying the multiplicative congruent method. The antithetic sampling technique is also used for variance reduction.
2) The classical two-state Markovian model is generally used to represent the system component operation while actual or equivalent generating units may be represented by a multiple state model in order to recognise their derated states. Common-cause transmission and distribution line outages may be also considered.
3) The generation system includes a number of plants while each plant consists of a number of single generating units.
4) The generating units can be taken out for scheduled maintenance during certain time periods of the year and their appropriate data are specified.
5) A generation rescheduling technique is applied after the occurrence of a generating unit outage for modifying the output of appropriate generating units in order to compensate for loss of generation.
6) Overloading of system branches is alleviated by scheduling the output of system generating units and/or load curtailment at appropriate system load-points. For this purpose, two appropriate algorithms may be used applying different criteria for load curtailment.
7) The network branch flows are obtained for any given hour of the simulation period using a DC load flow algorithm.
8) The production cost of the generation system is calculated by using the respective fuel consumption functions with regard to the power output of the appropriate generating units.

The prime objective of the above computational method is to calculate appropriate indices that quantify the operational and reliability performance of a power system. Two sets of reliability indices are calculated that refer to system adequacy. The first set forms load-point and system indices that reflect their respective adequacy. The second set forms load-point and system interruption indices that reflect the characteristics of the interruptions occurred. The following indices are considered to be the most important system and load-point indices while they have the corresponding units and acronyms in parentheses:

- Loss of load expectation (LOLE) in hours/year.
- Loss of energy expectation (LOEE) in kWh/year.
- Expected demand not supplied (EDNS) in kW/year.
- Frequency of loss of load (FLOL) in occ./year.
- Average duration of interruptions (DINT) in hours/occ.

It must be noticed that the above units of the reliability indices have been adopted appropriately in order to apply for low voltage distribution networks where microgrids are used.

4. Interruption Cost Functions of Power System Customers

Power system reliability is defined as its ability to provide an adequate and secure supply of electric power at any point in time [6, 9]. Supply interruptions, regardless of their cause or duration, deteriorate power system reliability and quality. Therefore, the analysis of the interruption cost for the different categories of customers is an important issue associated closely with justifying new facilities, quality and reliability of electric power systems. The impact of supply interruptions on the global cost and the quality of supply for a power system is shown in Figure 4.

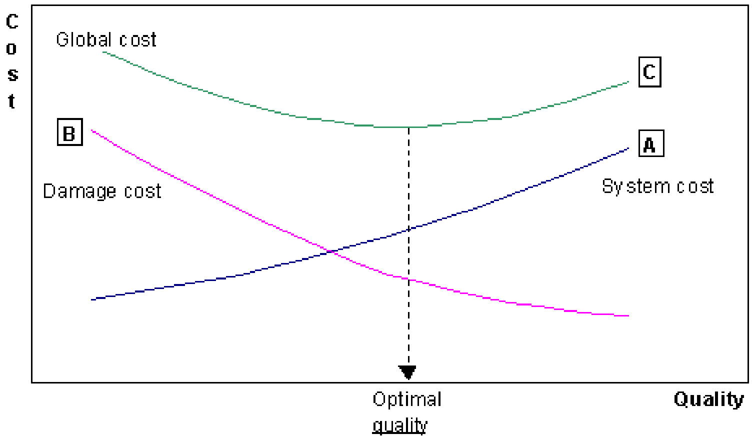

Figure 4: Impact of supply interruptions on the global cost of a power system

The ability to assess the power supply reliability has been well established [6, 9, 10, 11] while the ability to assess the interruption costs (worth of reliability) has been a subject of an increased number of publications during the last twenty years [12 - 16]. This assessment is a very difficult task to conduct directly and, alternatively, the costs and losses incurred by the customers as a result of a power supply interruption can be quantified more easily. These unreliability costs are not identical to the reliability worth but they can be considered as their representative and realistic measures since they constitute a lower bound.

It can be generally considered that the effects resulting directly from power supply interruptions constitute short-term effects as compared with the indirect effects, which tend to be considered as long term ones. The magnitude of all the direct effects is highly dependant on the characteristics of the customers (type of customer, energy dependency, size of operation, etc.) and on the characteristics of the interruption events (duration, frequency, time of occurrence, etc.). The customer survey approach has been utilised as the basic approach to investigate the direct short-term impacts and costs incurred by the electric power utility customers as a result of random supply interruptions [17]. The basis of this approach is that customers are in the best position to understand and assess how the costs due to supply interruptions impact their activities that depend upon electricity. During the last twenty years, interruption cost studies were conducted successfully in various countries and appropriate cost data were obtained for different categories of customers such as industrial, commercial, residential and agricultural [13, 14, 15, 16].

A customer survey approach was designed, carried out and utilised by the Electric Energy Systems Laboratory of the National Technical University of Athens (NTUA) in order to conduct an interruption cost assessment study of all the different sectors of power customers in Greece [15, 16]. This study presents the results that were obtained for the industrial and commercial sectors during the last three years. These results mainly include the interruption cost data and their variation according to the various characteristics of the interruption events and the power customers.

Two types of interruption costs are reported and they are known as the average cost per interruption (€/int) and the cost normalised by annual peak demand (€/kW) which is known as 'aggregated averages'. The aggregated average interruption cost is calculated as the ratio of the sum of interruption costs and the sum of the respective peak load demand for all customers. The approach of aggregated averages is used to offset the impact of small numbers for large or small customers, and the impact of small number of respondents who reported large or small costs. The estimates of the interruption cost are obtained from the direct cost assessment of the information being included in the respective cost questions of the questionnaires for each interruption duration being assumed. Therefore, interruption cost functions are determined for each customer category in a discrete form. Such functions have been reported assuming seven interruption durations (momentary, 3 minutes, 20 minutes, 1 hour, 2 hours, 4 hours, 1 day).

Appropriate interruption cost functions are available for all the major areas of activities for customers as it is shown in Table 1. As a small example, Figure 5 presents the overall Interruption Cost Functions for the three major categories of customers (industrial, commercial, agricultural) in Greece. Furthermore, Figure 6 presents the Interruption Cost Functions of the residential and certain types of agricultural customers in Greece.

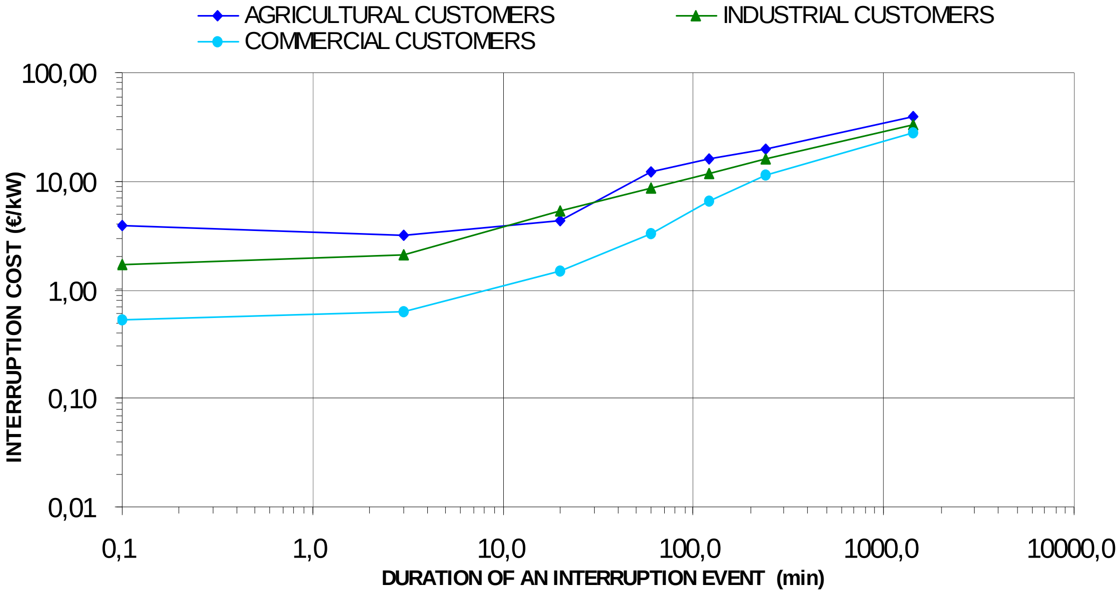

Figure 5: Overall Interruption Cost Functions for industrial, commercial and agricultural customers in Greece

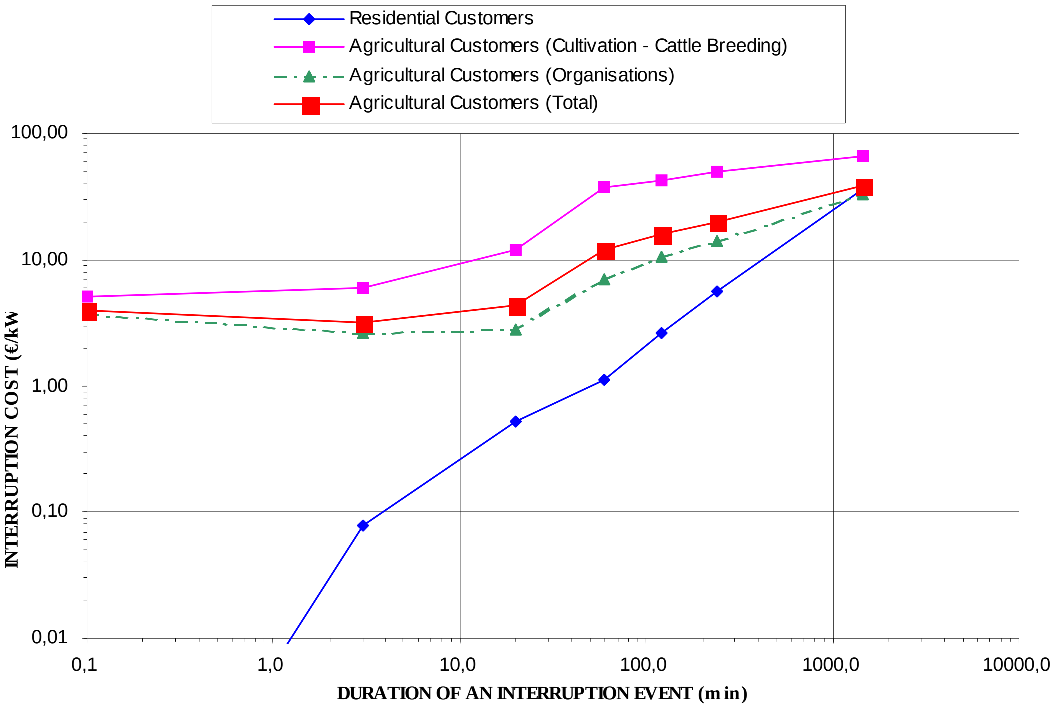

Figure 6: Interruption Cost Functions of residential and various types of agricultural customers in Greece

5. Reliability Modelling and Evaluation of Power Distribution Systems with Distributed Generation and Normally Open Switches

An improved and efficient computational methodology was developed for the reliability and cost assessment of power distribution systems that integrate distributed generation (DG) sources of various technologies. The operation of DG sources is simulated by the classical two-state Markovian model while their operational performance is quantified by taking into account the events which occur when they fail to produce their available output capacity due to their existing limitations (failure events, maintenance). This methodology also takes into consideration the failure events that may occur on the components of the distribution network by deducing the relevant topology of the network and identifying all subsystems being formed and the possible disconnection of the DG sources.

It is assumed that a number of wind parks can be installed at various geographical sites and each wind park consists of a certain number of groups of identical wind generating units. These wind parks are connected to the appropriate system nodes applying the existing connection rules. The average hourly wind speed of a geographical site is represented by an appropriate normal distribution which means that the values of the mean and standard deviation need to be given as input data for each hour of the year (8760 points). For simplicity reasons, the standard deviation may be assumed constant (e.g. 5%). The actual wind speed value for a particular simulated time period is determined by using appropriate random numbers. The available power output of a wind generating unit at any time period is calculated by using its appropriate curve expressing the power output in respect to the wind speed of the respective geographical site. The total wind power generation of the system at any simulation time period of the year is not allowed to exceed a certain fraction of the respective system load demand. This fraction expresses the wind penetration constraint (margin) being assumed in order to retain acceptable service reliability, security and efficient operation of the system supply source. If the total wind power generation of the system is higher than the limiting value, this generation level is necessary to be reduced. In this case, it is considered that an appropriate order will be given by the system control centre to each wind park to reduce its total power output by a certain amount so that the wind penetration margin is satisfied. This amount of power output is calculated by assuming that the same percentage of the total power output decrease is applied for all wind parks. As a result, it is assumed that a certain number of wind generating units in each wind park will be either disconnected from the system or decrease their power output by using appropriate procedures that take into account the technical characteristics of the respective units.

It is also assumed that a number of photovoltaic systems are installed at different geographical sites and are connected to appropriate system nodes by applying the existing connection rules. Each photovoltaic system consists of a certain number of groups of identical photovoltaic units. The average hourly solar radiation in a geographical site is represented by the normal distribution (or other more suitable distribution) while its actual value for a particular simulated time period is determined by using appropriate random numbers. Additional appropriate models have been developed and incorporated for modeling all necessary characteristics (slope, ground reflectance, temperature modification factor, soiling factor, etc.) for calculating the power output of each photovoltaic unit applying the solar radiation data of the respective geographical site.

The available power of the system supply source at any simulated time period is represented by an appropriate normal distribution which means that the values of the mean and standard deviation need to be given as input data. Its actual value for a certain time period is determined by using appropriate random numbers.

An appropriate algorithm was developed for simulating the dispatch procedures of system supply source and DG units in order to supply the respective load demand in each simulated time period. The available DG units (not being in either a repair or maintenance state) are only taken into account. It is considered that the available power output of photovoltaic systems and wind generating units (applying the existing penetration margin) supply the system load demand as a first priority since it is assumed that their operating cost is zero. The remaining load demand is usually allocated to the system supply source since its operating cost is expected to be lower than that of the microturbines and fuel cells. However, when its operational cost is greater than the respective cost of the available microturbines or fuel cells, these units are called on to operate first during the respective time periods. Finally, when the system supply source is inadequate to supply the remaining load demand and additional power generation is required due to failures being occurred, microturbines and fuel cells can be called on to operate in order to supply the remaining load demand according to their operating cost.

From the definition of the parameters concerning the electric energy storage systems (ESS), it is obvious that in each simulated time period their energy storage level C must always lie between their minimum and maximum values (C_{min} and C_{max}). Additionally, the charging and the discharging modes of operation can start according to the operating features of the power supply system when $C<k{\cdot}C_{max}$ and $C>w{\cdot}C_{max}$ respectively. Furthermore, it is considered that the decision for the installation and operation of ESS in power distribution networks implies that their charging cost is kept very low so that their use is effective. For this purpose, the available system generation with very low production cost must only be used for charging purposes when adequate power is available. The respective generating units must be specified accordingly. Finally, when the ESS are used for decreasing the system production cost, the operation of the relevant system generating units with high production costs must be affected and they must be specified accordingly.

An additional algorithm was incorporated in the developed methodology in order to simulate the dispatch procedures of system generating units in the cases when failure events occur on the network components and the respective system branches are isolated. The system topology is deduced by identifying the configuration of the new subsystems being created and by calculating their respective load demand and generation capacity. When the load demand of each subsystem is satisfied by the local generation, it is considered that no switching actions of normally open switches are performed. However, if additional power is required for satisfying the load demand of certain subsystems, the appropriate normally open switches connecting adjoining feeders are deduced and their energisation provides alternative routes of power flow. This operating procedure results to the supply of either a part or the total system load demand that would otherwise had to be curtailed. The operation of normally open switches is determined by taking into account the minimisation of the required system operating actions. In addition, it is assumed that the system operating actions of all normally open switches are performed by using appropriate telecontrolled facilities and a suitable time period is required (i.e. 10 minutes). Finally, a suitable stuck probability is also taken into account.

The available spinning reserve of the system for each simulated time period is calculated by taking into account the operational features of system generation during the previous time period. For this purpose two criteria are used. Criterion 1 assumes that the spinning reserve is equal to a certain percentage of the total wind power generation in order to compensate sudden losses of this output in case of very fast wind speed changes. Criterion 2 assumes that the spinning reserve is equal to a certain percentage of total system load demand in order to compensate for a sudden loss of system supply sources (reliability criterion). The actual value for the spinning reserve is calculated as the greatest value being obtained by using the two criteria.

The system reliability worth is quantified by calculating a set of appropriate indices that take into account the interruption cost functions of the various categories of system customers. An efficient algorithm is incorporated into the developed methodology that has the following main steps:

- For each contingency that leads to a load curtailment at each system node the magnitude of load curtailment and the duration of contingency are calculated.
- The expected interruption cost to customers ECOST (in €/year) that are connected at each system node is calculated using its composite interruption cost function. This function is determined by taking into account the respective functions of all the customer categories being connected to the node.
- The expected interruption cost of the entire system ECOSTT (in €/year) is calculated by adding the respective costs of all customers being connected to the nodes of the system.
- The interrupted energy assessment rate IEARN in Euro/kWh at each node is calculated as the ratio of indices ECOST and LOEE for the node.
- The system interruption cost rate IC (in €/hour) is calculated as the ratio of indices ECOSTT and LOLE for the entire system.
- The system index of IEARS (in Euro/kWh) is calculated by adding the products of index IEARN of each node and its fraction of system load being taken.

Using the above described computational methodology, the following additional system indices are calculated which have the corresponding units and acronyms in parentheses:

a) Six indices quantifying the system generation capability:

- Expected total energy supplied by all the generating units of the system (EGSM) in MWh/year.
- Expected total energy supplied by the system supply source (EGNT) in MWh/year.
- Expected total energy supplied by the generating units of various DG sources (EGDG) in MWh/year.
- Expected energy supplied by wind generating units (EGWT) in MWh/year.
- Expected energy supplied by photovoltaic generating units (EGPV) in MWh/year.
- Expected energy supplied by fuel cells (EGFC) in MWh/year.
- Expected energy supplied by microturbines (EGMT) in MWh/year.

b) Five indices quantifying the operational performance of the overall generation capability of DG sources, each type of DG sources and each individual DG source site by taking into account the events that may occur (failures, maintenance). These indices have the respective acronyms (WT – wind, PV – photovoltaics, FC – fuel cells, MT – microturbines, DG - overall):

- Expected energy not supplied during the events being occurred (ENSWS, ENSWM) in kWh/year.
- Expected annual duration of the events being occurred (DNSWS) in hours/year.
- Expected load demand not supplied during the events being occurred (PNSWS) in kW/occ.
- Frequency of events being occurred (FNSWS) in occ./year.

c) Six indices quantifying the operational capability of the energy storage systems (ESS):

- Expected energy not supplied during the events being occurred (ENSWS, ENSWM) in kWh/year.
- Frequency of charging events (FBTC) in occ./year.
- Annual duration of charging events (ADTC) in hours/year.
- Expected energy being required by the ESS (EBTC) in MWh/year.
- Frequency of discharging events (FBTD) in occ./year.
- Annual duration of discharging events (ADTD) in hours./year.
- Expected energy supplied by the ESS (EBTD) in MWh/year.

d) Three indices quantifying the available spinning reserve by applying the respective criterion:

- Available spinning reserve (AVSPRES) as a percentage of the respective load demand.
- Percentage of applying Criterion 1 for evaluating spinning reserve (FWIND).
- Percentage of applying Criterion 2 for evaluating spinning reserve (FLOAD).

e) Two indices for system reliability worth

- Interruption Cost (IC) in Euro/hour.
- Interrupted energy assessment rate of the system (IEARS) in Euro/kWh.

f) Four indices quantifying the system operation by taking into consideration the switching actions for the energisation of normally open switches:

- Frequency of such events (FSWAC) in occ./year.
- Annual duration of such events (DSWAC) in hours/year.
- Average duration of such events (ADSWAC) in hours.
- Average number of switching actions being performed in each event (NSWAC).

It must be noticed that the above units of the reliability indices have been adopted appropriately in order to apply for low voltage distribution networks where microgrids are used

6. Assessment Studies

The developed computational methodology was applied for conducting reliability assessment studies on the typical power distribution system which has the single line diagram shown in Figure 7. The system peak load demand is equal to 190 kW. The network consists of three feeders that supply commercial, residential and industrial customers while three normally open switches exist that connect the adjoining feeders. The required time period for the relevant switching actions is equal to ten minutes while a stuck probability is considered that it is equal to 2%. A certain number of DG sources exists using various technologies. One wind turbine exists with generating capacity equal to 15 kW and two photovoltaic parks are installed at two different system sites with five generating units having various power output capacities and total generating capacity being equal to 13 kW. Additionally, there are one microturbine and one fuel cell with generating capacity equal to 30 kW each. The operating cost function of the system source is shown in Figure 8 for one typical day of the year. These hourly values represent the respective average values for all the year. It is assumed that the coefficients for the operating cost for the microturbines and fuel cells are A=0.01, B=5.16, C=46.1 for microturbines and A=0.01, B=3.04, C=130 for fuel cells.

This system provides a good example for illustrating the different operating features of DG sources. However, this report is mainly concerned with the study of the impact of normally open switches on the reliability performance of the system. For this purpose, only the impact of their operating features on the system reliability indices is studied and seven case studies were considered that model these features. The base case study (Case 1) assumes that the capacity of the system supply source follows a normal distribution with an average value equal to 100% of the system peak load demand and a standard deviation equal to 5%. No wind penetration margin and no criteria for spinning reserve are applied. The full set of system indices were evaluated for the following seven case studies and the obtained results are presented in Table 2:

Case 1: Base case study assuming that no normally open switches exist.

Case 2: As in case 1 but one normally open switch exists (switch 1).

Case 3: As in case 1 but two normally open switches exist (switches 1, 2).

Case 4: As in case 1 but three normally open switches exist (switches 1, 2, 3).

Case 5: As in case 4 but the required time period for the switching actions decreases to three minutes.

Case 6: As in case 4 but the required time period for the switching actions increases to twenty minutes.

Case 7: As in case 4 but the stuck probability of normally open switches increases to 5%.

A considerable number of comments can be drawn from the results of Table 2 but the most important ones are the following:

- The energisation of normally open switches improves significantly the reliability performance of the system. The LOEE index is decreased by approximately 56% while the LOLE index is decreased by approximately 28% as it can be noticed by comparing the results of the Cases 1 and 4. The reliability indices concerning the Cases 2 and 3 have values that lie between the two extremes.
- The installation of additional normally open switches has always a positive impact on the reliability performance of the system as there are more available alternative routes for power flow. This can be noticed by comparing the results of Cases 1 to 4 concerning the reliability indices. However, the average number of switching actions being performed in the relevant events is almost equal to one in all case studies, which means that only one normally open switch is being

energised on average in each event, regardless of the total number of normally open switches being available.

- The technical and operational features of the normally open switches being installed (stuck probability and required time for switching actions) have a minor effect on the reliability performance of the system since the results of Cases 4 to 7 concerning the reliability indices show very small variations.
- The total energy being supplied by the system generating units increases with the installation of additional normally open switches. This is due to the fact that all units are called on to operate in order to supply the remaining load demand of other subsystems when the appropriate switches are energised. The greatest part of the additional energy is supplied by the system supply source. This is because the generating units using renewable energy sources are called on to operate in all time periods being permitted by their technical and operational characteristics and the topology of the system is not taken into consideration.
- The index of the system interruption cost rate is decreased by 24% due to the installation of additional normally open switches and the subsequent significant decrease of the expected demand not supplied (EDNS index) and the average duration of interruptions (DINT index). However, the interrupted energy assessment rate increases because the relative decrease of the expected energy not supplied (LOEE) is greater than that of the expected interruption cost of the system (ECOSTT) for each case study.

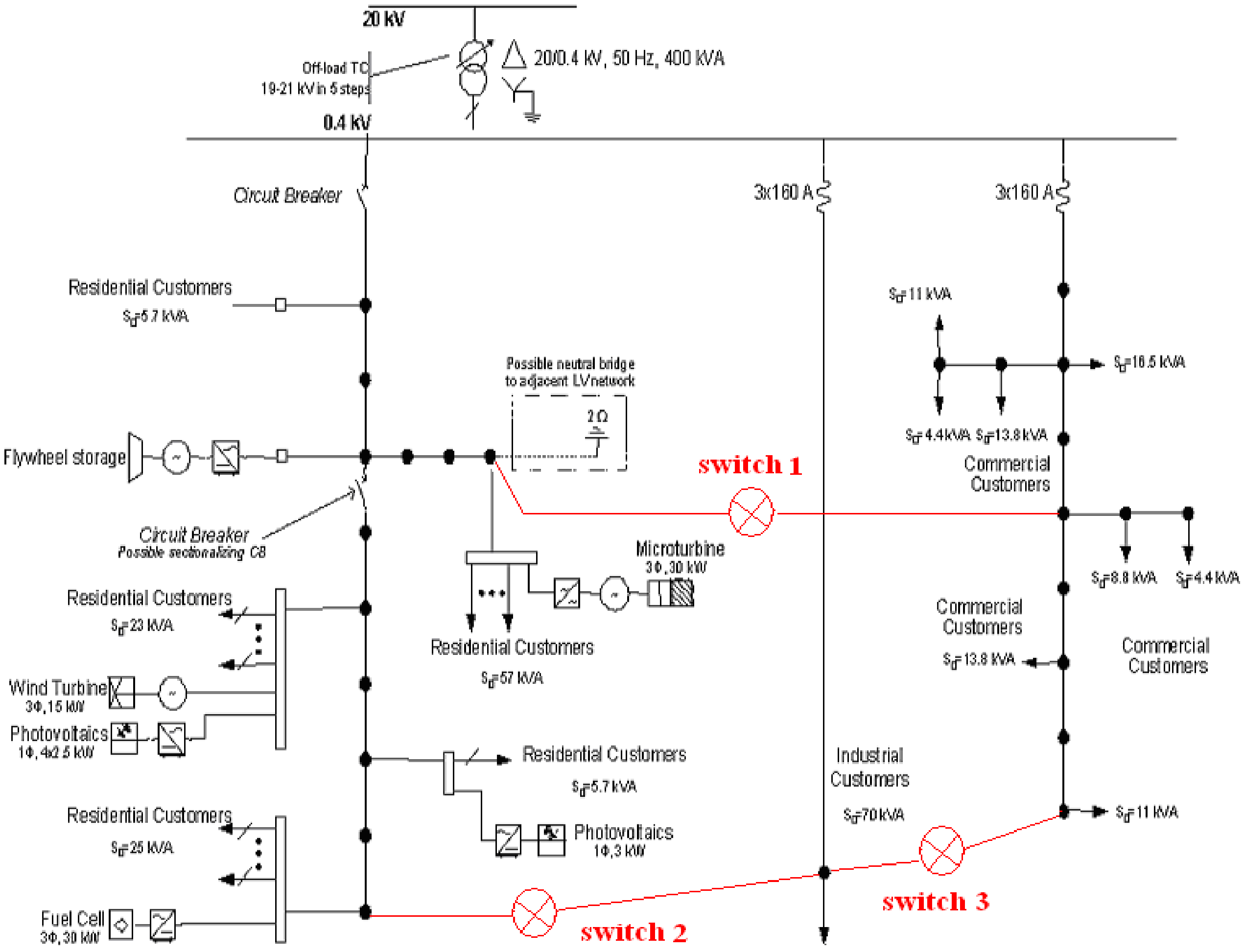

Figure 7: Single line diagram of the typical power distribution system with distributed generation sources and multiple feeders being connected with normally open switches

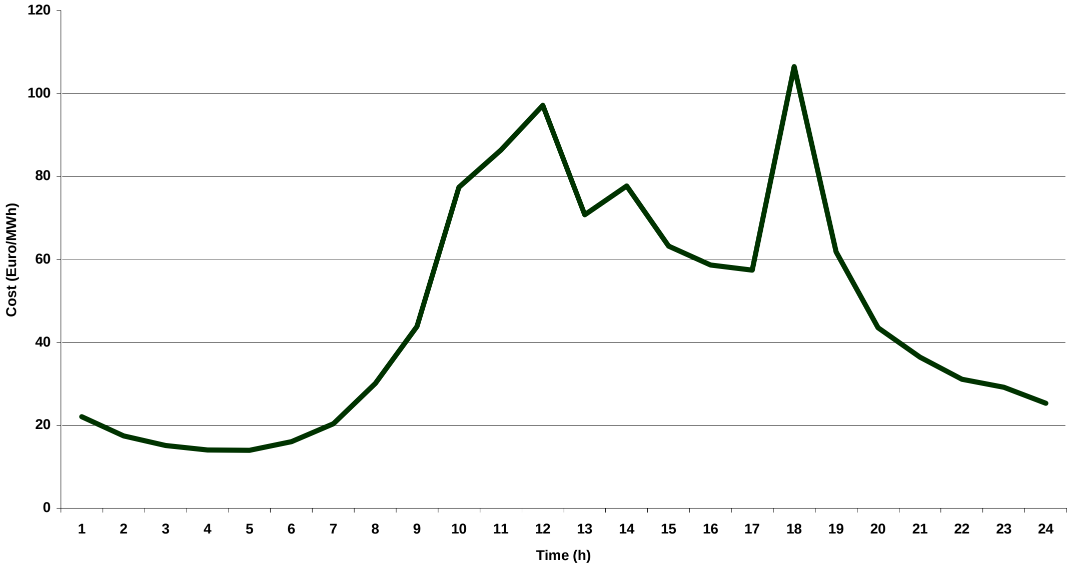

Figure 8: Operating cost function of the system supply source for one typical day of the year

Table 2: System Reliability Indices showing the impact of normally open switches on system operation

Case Study Index	1	2	3	4	5	6	7
LOLE	384.01	355.94	317.74	277.71	276.43	279.53	278.01
LOEE	5827.529	4349.041	3016.965	2587.271	2540.353	2654.297	2593.015
EDNS	15.025	12.136	9.569	9.407	9.279	9.586	9.413
FLOL	26.38	26.28	27.37	27.80	27.80	27.80	27.80
DINT	14.55	13.54	11.61	9.94	9.94	10.06	10.0
EGSM	833.573	835.092	836.444	836.880	836.881	836.881	836.876
EGNT	697.752	699.005	700.242	700.233	700.234	700.234	700.230
EGDG	135.821	136.087	136.202	136.647	136.647	136.647	136.645
EGWT	93.497	93.355	93.337	93.521	93.521	93.521	93.521
EGPV	21.666	21.668	21.667	21.665	21.665	21.665	21.665
EGFC	10.208	10.551	10.699	10.755	10.755	10.755	10.754
EGMT	10.450	10.513	10.499	10.706	10.706	10.706	10.705
FSWCAC	-	9.14	11.19	15.41	15.41	15.41	15.33
DSWAC	-	91.14	136.94	201.38	201.38	201.38	200.94
ADSWAC	-	9.97	12.23	13.07	13.07	13.07	13.11
NSWCAC	-	1.0	1.16	1.12	1.12	1.12	1.12
ECOSTT	7514.692	6190.508	4786.435	4133.158	3935.534	4341.380	4150.689
IC	19.569	17.392	15.064	14.883	14.237	15.531	14.930
IEARS	1.290	1.423	1.586	1.597	1.549	1.636	1.601

7. Conclusions

One of the most important aspects of the competitive electric energy market is the operation of independent power producers that can be connected at any system voltage level. The increased use of renewable sources and more advanced technologies may significantly affect the operational characteristics and inevitably the reliability performance of power systems. This report describes the main concepts and features of an improved computational methodology that is based on the sequential Monte – Carlo simulation approach and simulates efficiently and realistically all the features of distributed generation sources that can be connected to a distribution system (microgrids). An effective algorithm is incorporated in the methodology in order to simulate the operating procedures that can be performed after the occurrence of failure events on the network components by identifying the new subsystems being created. These procedures concern the use of normally open switches through loop power flow controllers and they can provide alternative routes of power flow when it is required. The report also presents the results that were obtained from the reliability assessment studies conducted for a power distribution system which is based on a typical power system with multiple feeders being connected with normally open switches. The obtained results demonstrate clearly that the system adequacy is significantly dependent on the switching procedures of the normally open switches. In addition, it is shown that the number of the normally open switches being installed and their operational features also affect the reliability performance of the system.

8. References

1. Shahidehpour, M., Alomoush, M., “Restructured Electrical Power Systems”, Marcel Dekker, New York, 2001.
2. Shahidehpour, M., Yamin, H., Li, Z., “Market Operations in Electric Power Systems”, Wiley, New York, 2002.
3. Jenkins, N., Allan, R., Crossley, P., Kirschen, D., Strbac, G., “Embedded Generation”, IEE Publications, London, 2000.
4. “MICROGRIDS – Large Scale Integration of Micro-Generation to Low Voltage Grids”, EU Contract ENK5-CT-2002-00610, Technical Annex, May 2002, also at http://microgrids.power.ece.ntua.gr
5. Okada, N., Takasaki, M., Shiina, T., “Loop Distribution System with LPC and its Planning Method”, 2007 CIGRE Symposium, Paper 503, Osaka, November 2007.
6. Billinton, R., Allan, R. N., "Reliability Assessment of Large Electric Power Systems", Kluwer Academic Publisher, Accord Station, New York, 1988.
7. Anders, G. J., Endrenyi, J., Pereira, M. V. F, Pinto, L., Oliveira, C., Cunha, S., “Fast Monte – Carlo Simulation Techniques for Power Systems Reliability Studies”, 1990 CIGRE Session, Paris, Paper 38-205.
8. Dialynas, E. N., Koskolos, N. C, "Comparison of Contingency Enumeration and Monte - Carlo Simulation Approaches Applied to the Reliability Evaluation of Composite Power Systems", European Journal of Diagnosis and Safety in Automation, Hermes, Vol. 5, 1995, pp. 25 - 48.
9. Billinton R., Allan R.N.,. “Reliability Evaluation of Power Systems”, Plenum Press, New York, 1984.
10. Allan R.N., Billinton R., Breipohl A.M., Grigg C.H., , “Bibliography on the Application of Probability Methods in Power System Reliability Evaluation, 1987-1991”, IEEE Transactions, Vol. PWRS-9, pp. 41 – 49, 1993.
11. Billinton, R., Fotuhi – Firuzabad, M., Bertling, L., “Bibliography on the Application of Probability Methods in Power System Reliability Evaluation 1996 – 1999”, IEEE Transactions, Vol. PWRS – 16, 2001, pp. 595 – 602.
12. Tollefson G., Billinton R., Wacker G., “Comprehensive Bibliography on Reliability Worth and Electrical Service Interruption Cost: 1980-1990”, IEEE Transactions, Vol. PWRS-6, pp. 1508 – 1514, 1991.
13. Tollefson G., Billinton R., Wacker G., Chan E., Aweya J., “Canadian Customer Survey to Assess Power System Reliability Worth”, IEEE Transactions, PWRS-9, pp. 443 – 450, 1994.
14. Kariuki K.K., Allan R.N., Palin A., Hartwright B., Caley J., “Assessment of Customer Outage Costs due to Electricity Service Interruptions”, CIRED ’95, Paper 2.05, 1995.
15. Dialynas, E. N., Megalokonomos S.M., Dali V.C., “Interruption Cost Analysis for the Electrical Power Customers In Greece”, CIRED 2001, Amsterdam 2001.
16. Megalokonomos S.M., Dialynas, E. N., Dali V.C., “Interruption Cost Analysis for the Agricultural Electrical Power Customers in Greece”, MedPower 2002, Athens, 2002.
17. Dillman D.A., “Mail and Telephone Surveys”, John Wiley and Sons, New York, 1978.