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PROBABILISTIC METHODOLOGY TO DETERMINE THE IMPACT OF DISPERSED GENERATION ON THE RELIABILITY WORTH OF POWER DISTRIBUTION NETWORKS

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SUMMARY

In recent years, electrical 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. One of the most important aspects of the competitive electrical energy market is the operation of independent power producers that can be connected at any system voltage level. This new environment concerns dispersed generation where the customers own their generating units becoming both producers and consumers of electricity.

The objective of the paper is to describe an improved and efficient computational methodology that was developed for evaluating the reliability worth of dispersed generation in power distribution networks. The dispersed generating units mainly use renewable energy sources (photovoltaic and wind generating units) and a broad range of advanced technologies, such as fuel cells and microturbines. This methodology is based on a Monte - Carlo sequential simulation approach. The basic features of this methodology include the recognition of the appropriate interruption costs for the different system busbars that may supply various categories of customers and the consideration of the duration of system contingencies that may occur. An increased emphasis is given in the realistic and efficient representation of the real design and operational features and practices applied in the distribution networks such as the modelling of the dispersed generating units and the operation of dispersed generation in parallel with the high-voltage transmission system that is considered to be the normal supply source of the system. The paper also presents the analysis of a typical low voltage network with multiple feeders supplying different categories of customers (industrial, commercial and residential) and assuming alternative system planning schemes. These schemes include different operating conditions of power generating units such as the different penetration levels of the renewable sources. The obtained results are presented and discussed.

KEYWORDS

Dispersed Generation – Microgrids - Renewable Energy Sources – Microturbines - Fuel Cells - Reliability Assessment - Monte Carlo Simulation - Reliability Worth

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1. INTRODUCTION

During the recent years, there is an increased demand for a better quality level concerning the power supply to customers while small and medium size generating units based on renewable energy sources and more advanced technologies have started being introduced in distribution systems [1, 2]. This new environment concerns a new model for the power systems that is known as Dispersed Generation (DG), where the customers will own their generating units becoming both producers and consumers of electricity. The electrical distribution systems that connect multiple customers to multiple dispersed sources of generation and storage are capable of supplying small-scale power at sites close to consumers and may provide them with continuous and reliable supply, when power outages occur. The quantification of the impact that the dispersed generation sources have on the reliability of customers supply is an important aspect in planning studies of electrical distribution networks. This is a challenging task due to the distribution systems complexity. For this purpose, additional studies are necessary to be conducted which will be based on probabilistic system modelling and consider the loss of loads and their associated costs. In order to examine the economics of reliability in a power system, it is necessary to estimate the reliability level and its associated costs and to determine the worth of power supply to the customers with its associated financial value [3].

The present paper is concentrated in power distribution systems and its major objective is to assess the impact of dispersed generation on their reliability performance taking into account the principles of competitive electrical energy market [4]. It is assumed that these systems are connected to transmission systems through appropriate substations while additional power generating units are assumed to 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 dispersed generation in parallel with the high-voltage transmission supply system and its performance during abnormal conditions such as power supply outages.

An improved and efficient computational methodology was developed for calculating the reliability and operational indices of distribution systems incorporating dispersed generation. 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 dispersed generating units and system customer categories. An analysis is also included that was conducted using a typical low voltage distribution network that incorporates dispersed generating units of various technologies (Microgrids) [5] while it consists of multiple feeders supplying different categories of customers (industrial, commercial and residential). This analysis assumes alternative system planning schemes that take into account the different operating conditions of power generating units, such as the different penetration levels of the renewable sources and the different capacity levels of the system supply source. All the case studies being examined take into account the power interruption costs that were estimated through a customer survey being conducted in Greece.

2. MAIN FEATURES OF DISTRIBUTION SYSTEMS AND DISPERSED GENERATION

The reliability assessment of power distribution systems requires appropriate modelling of their features that affect their operation and, especially, the features of dispersed generation. The most important issues that require a further investigation are the system topology, the customers' profiles and the operational characteristics of the dispersed generation sources. In a generic representation of a distribution system with dispersed generation, one or more feeders are connected to a substation that 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 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 substation. The system supply source is considered to have an operating cost function 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).

The nodes of the distribution networks can either be simple nodes or customer nodes. Each customer node supplies customers of certain categories that can be industrial, commercial, agricultural and residential customers. Table 1 presents the major areas of activities for each of the first three categories of customers. The system load demand requirements are determined by the peak load demand of each system customer node, 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 for residential, commercial and industrial customers respectively.

Table 1: Major areas of activities for customer categories

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

In the modern competitive electrical energy market, various dispersed generation sources may exist with different technological and operational characteristics. They can be located anywhere within the distribution network and they are connected either to a simple node or a customer node. Dispersed 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 plants, back up and peak load systems are providing increasing capacity. In this paper four different technologies (wind generating units, microturbines, fuel cells and photovoltaics) are considered and their impact on the reliability performance of distribution networks is assessed.

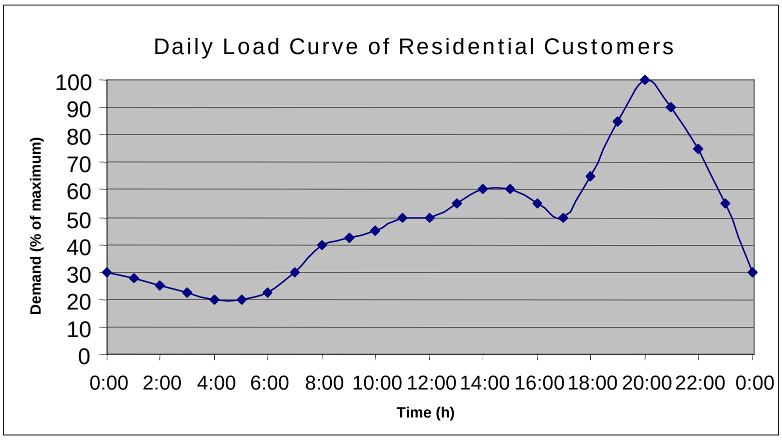

Figure 1: Typical daily load demand curve of residential customers

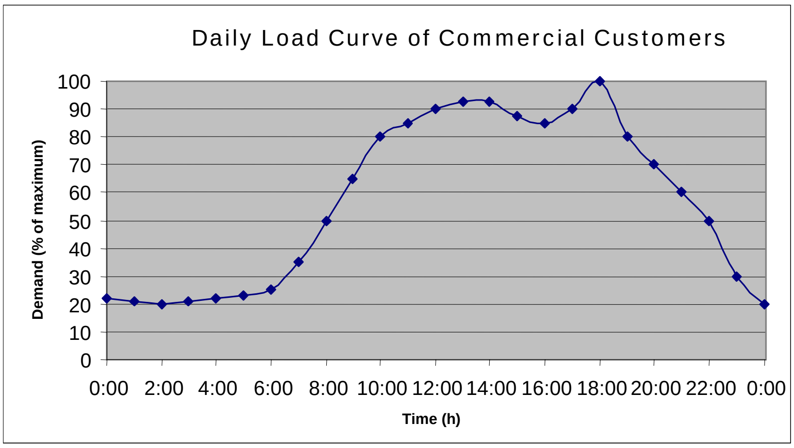

Figure 2: Typical daily load demand curve of commercial customers

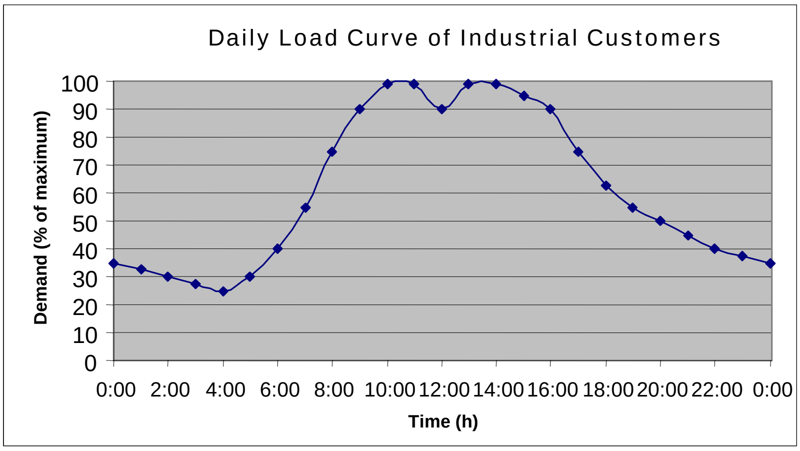

Figure 3: Typical daily load demand curve of industrial customers

Wind generating units are based on wind turbines that 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, storage systems or other types of generation must supply any power requirements in excess of the wind power. Because they commonly use induction generators, small wind systems are not easily adapted to Microgrid operation unless other sources supply voltage and frequency control.

Microturbines are composed of a generator and a small gas turbine mounted on a single shaft. Most microturbines are fuelled by natural gas but they can also use liquid fuels such as diesel or jet fuel. These units currently range in size 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 are an attractive power generation technology because of their potential for highly effective conversion to electrical power. The technology of phosphoric acid fuel cell is in general use today and it is available in the 200kW size range. A number of other fuel cell technologies are being developed such as proton exchange membrane (low temperature, hydrogen fuelled), molten carbonate (high temperature), and solid oxide (high temperature). 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 rely on sunlight to produce DC voltage at cell terminals that depends on the intensity of sunlight and the design of the cell. Photovoltaics, like microturbines and fuel cells, generate DC voltage that must pass through an inverter to produce alternating current for distribution on the utility grid. Storage is required for stand - alone systems if power requirements exceed available sunlight.

By taking into account the above described main characteristics of the dispersed 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, dispersed generation sources are assumed to 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 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, dispersed 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.

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 paper. 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.

3) The generation system includes a number of plants while each plant consists of a number of single generating units.

4) It is considered that the generating units are 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.

4. INTERRUPTION COST FUNCTIONS OF POWER SYSTEM CUSTOMERS

Power system reliability is defined as its ability to provide an adequate and secure supply of electrical power at any point in time. 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 electrical power systems. The ability to assess interruption costs (reliability worth) has been a subject of an increased number of publications during the last twenty years [3, 9 - 12]. 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.

The effects resulting directly from power supply interruptions are generally considered to be 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 dependent 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. 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 [3, 9 - 12]. A customer survey approach was designed, carried out and utilised by the 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 [11, 12].

Two types of interruption costs are reported and they are known as the average cost per interruption (Euro/int.) and the cost normalised by annual peak demand (Euro/kW) that 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. 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 an example, Figure 4 presents the overall Interruption Cost Functions for the three major categories of customers (industrial, commercial, agricultural) in Greece while Figure 5 presents the Interruption Cost Functions of the residential and certain types of agricultural customers in Greece.

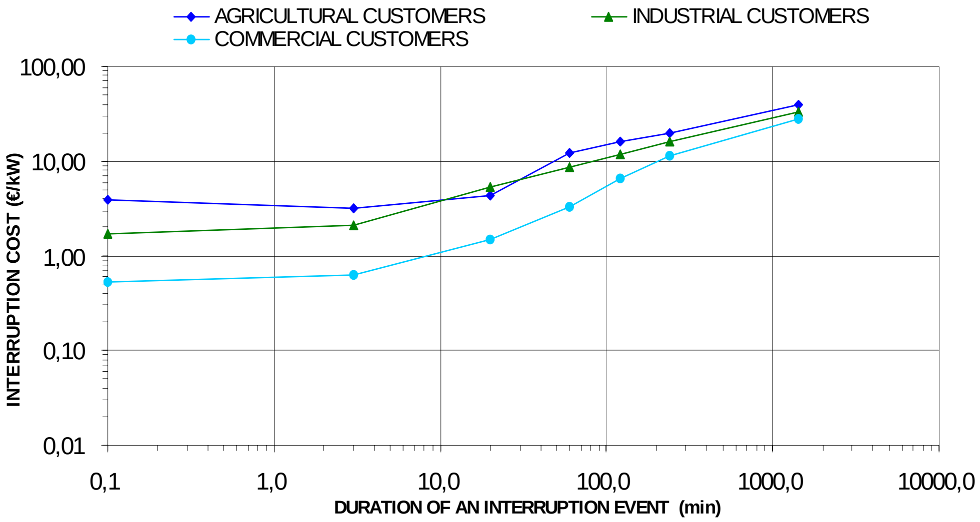

Figure 4: Interruption Cost Functions for industrial, commercial and agricultural customers in Greece

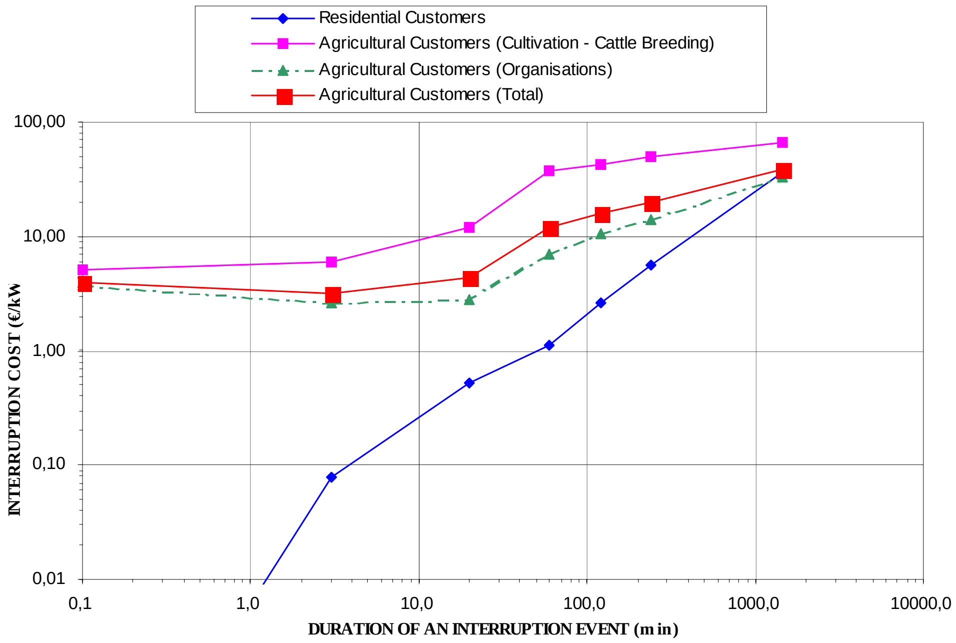

Figure 5: Interruption Cost Functions of residential and agricultural customers in Greece

5. RELIABILITY MODELLING AND EVALUATION OF POWER DISTRIBUTION SYSTEMS WITH DISPERSED GENERATION

An improved and efficient computational methodology was developed for the reliability and cost assessment of power distribution systems that integrate dispersed 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). Failure events on the components of the distribution networks are not considered since the respective feeder is disconnected from the system causing the loss of supply to all respective customers and the disconnection of all relevant DG sources.

It is assumed that 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 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 assuming that the same percentage of the total power output is applied for each park. As a result, a certain number of wind generating units in each wind park are assumed to be either disconnected from the system or decrease their power output using appropriate procedures that take into account the technical characteristics of the respective units.

Photovoltaic systems are assumed to be installed at different geographical sites and are connected to appropriate system nodes 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 modelling 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 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 simulation time period. The available DG units (not being in a repair or maintenance state) are only taken into account. The available power output of photovoltaic systems and wind generating units (applying the existing penetration margin) are assumed to 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 are called on to operate in order to supply the remaining load demand according to their operating cost.

The available spinning reserve of the system for each simulation 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 source (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 customers' categories of the system. An efficient algorithm is incorporated into the developed methodology having 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 Euro/yr) that are connected at each system node can be obtained 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 system interruption cost IC (in Euro/yr) can be calculated by adding the respective indices ECOST for all system nodes.
- The interrupted energy assessment rate IEARN in Euro/kWh at each node can be calculated as the ratio of indices ECOST and LOEE for the node.
- The system index of IEARS (in Euro/kWh) can be obtained 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 the system supply source (EGSM) in MWh/year
- Expected total energy supplied by the generating units of various DG sources (EGWS) 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 system DG sources, each type of DG sources separately and each individual DG source site separately by taking into account the events that may occur (failures, maintenance). These events consider that at least one DG unit is not in operation. Furthermore, 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) 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).

d) Two indices for system reliability worth

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

6. ASSESSMENT STUDIES OF A TYPICAL SYSTEM

The developed computational methodology was applied for conducting reliability assessment studies on the typical power distribution system that has the single line diagram shown in Figure 6. There are three feeders supplying residential, commercial, and industrial customers that have the daily load demand curves shown in Figures 1, 2 and 3 respectively. The total system load demand is equal to 233 kW with a peak value equal to 190 kW. 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 units having various power output capacities and a total capacity equal to 13 kW. Additionally, there are one microturbine and one fuel cell with a generating capacity equal to 30 kW each. The operating cost function of the system supply source is shown in Figure 7 for one typical day of the year. These hourly values represent the respective average values for the whole year. The coefficients for the operating cost are assumed to be A=0.01, B=5.16, C=46.1 for the microturbines and A=0.01, B=3.04, C=130 for the fuel cells.

This system provides a good example for illustrating the different operating features of DG sources. The base case study assumes that the capacity of the system supply source follows a normal distribution with an average value equal to 190 kW (100% of the system peak load demand) and a standard deviation equal to 5% while no wind penetration margin and no criteria for spinning reserve are applied. The full set of system indices was calculated for the following nine alternative case studies and they are presented in Table 2:

Case 1: Base case study

Case 2: As in case 1 but the average value for the capacity of the system supply source decreases to 152 kW (80% of the system peak load demand).

Case 3: As in case 1 but the average value for the capacity of the system supply source decreases to 133 kW (70% of the system peak load demand).

Case 4: As in case 2 but the total capacity of wind generating units increases by 15 kW (100%).

Case 5: As in case 1 but the total capacity of wind generating units increases by 30 kW (200%) and a wind penetration margin equal to 15% is applied. The available spinning reserve is calculated assuming a percentage equal to 100% of total wind power generation according to Criterion 1 and a percentage equal to 10% of the system load demand according to Criterion 2.

Case 6: As in case 1 but the system load demand increases by 30 kW (12.88% increase in the load demand of each system node). The system peak load demand becomes 214.50 kW (increase by 24.5 kW). Additionally, the total capacity of wind generating units increases by 30 kW (200%).

Case 7: As in case 6 but the total capacity of wind generating units remains the same as in case 1 and, instead, the total capacity of microturbines increases by 30 kW (100%).

Case 8: As in case 6 but the total capacity of wind generating units remains the same as in case 1 and, instead, the total capacity of fuel cells increases by 30 kW (100%).

Case 9: As in case 6 but the total capacity of photovoltaic systems increases by 30 kW (230%).

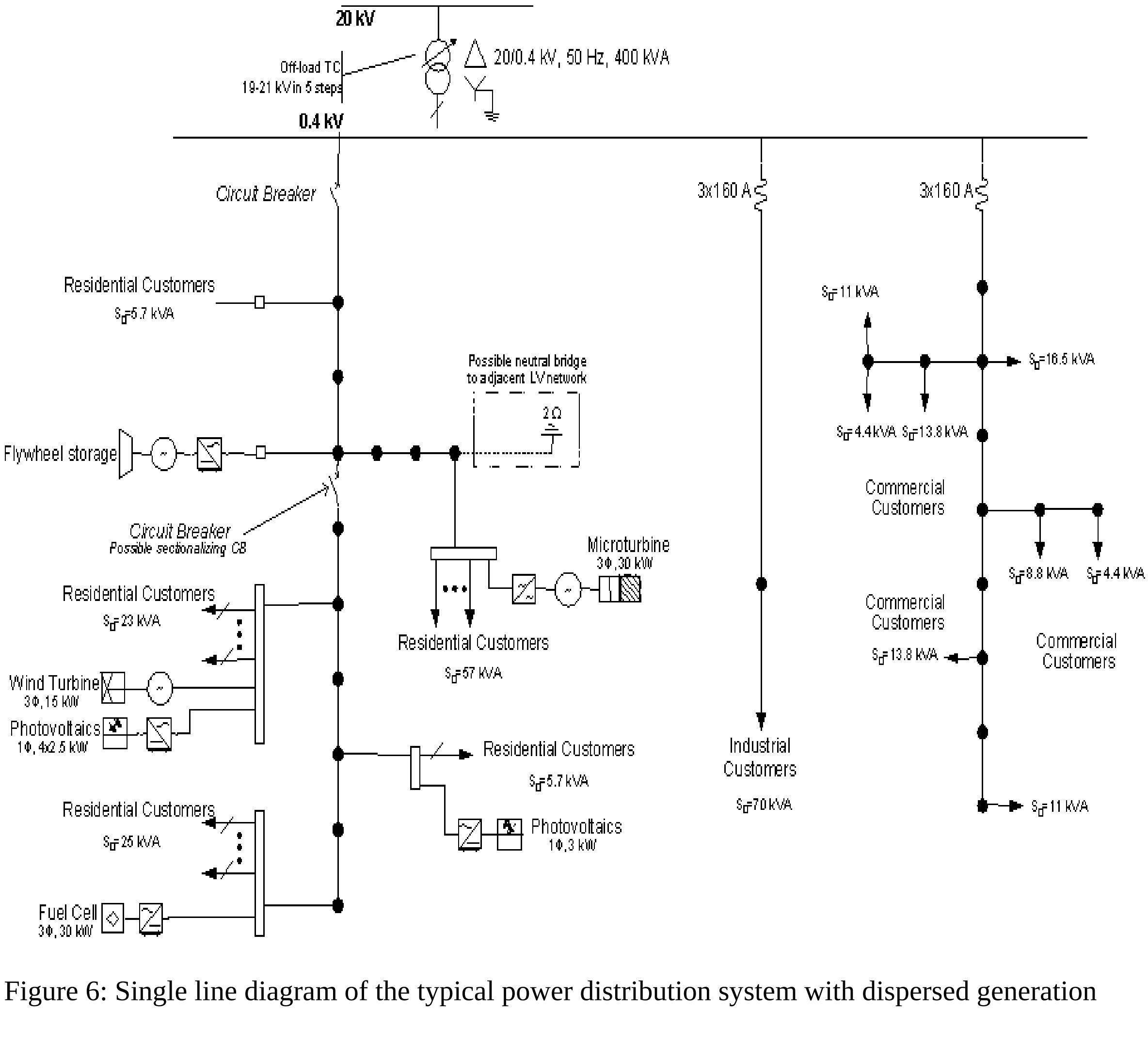

Figure 6: Single line diagram of the typical power distribution system with dispersed generation

Table 2: System Reliability Indices

Case Study / Index	1	2	3	4	5	6	7	8	9
LOLE	16.120	16.209	17.708	14.743	16.492	14.671	14.270	14.156	13.617
LOEE	743.737	744.168	753.134	554.213	653.635	606.336	547.639	539.782	493.163
EDNS	36.22	36.06	33.52	28.80	31.07	31.74	29.21	28.97	27.06
FLOL	2.273	2.342	3.388	2.206	2.262	2.191	2.142	2.149	2.171
DINT	7.092	6.921	5.227	6.683	7.291	6.696	6.662	6.587	6.272
EGSM	660.507	660.059	657.010	553.499	643.087	554.470	743.712	745.849	508.050
EGWS	178.150	178.599	181.638	285.348	195.661	392.369	203.184	201.054	438.899
EGWT	107.341	107.341	107.341	214.714	124.823	321.863	107.377	107.370	321.433
EGPV	20.945	20.945	20.945	20.945	20.945	20.944	20.945	20.946	68.434
EGFC	23.254	23.271	23.439	23.076	23.269	23.074	22.995	46.086	22.567
EGMT	26.610	27.042	29.913	26.613	26.624	26.487	51.868	26.673	26.465
ENSWS-WT	6742.51	6742.51	6742.51	13455.20	12022.48	197.70	6715.71	6721.86	20.19
ENSWM-WT	4701.79	4701.79	4701.79	9398.73	7618.64	14090.46	4696.96	4692.84	14074.82
DNSWS-WT	496.485	496.485	496.485	965.650	1427.330	1374.980	494.590	494.960	1404.715
PNSWS-WT	13.571	13.571	13.571	13.724	7.975	13.950	13.584	13.568	13.947
FNSWS-WT	5.059	5.059	5.059	9.464	13.487	13.180	5.189	5.078	13.590
ENSWS-PV	859.80	859.80	859.80	859.8	859.81	859.91	859.81	859.88	2780.82
ENSWM-PV	46.82	46.82	46.82	46.83	46.84	46.84	46.85	46.85	143.62
DNSWS-PV	1581.40	1581.40	1581.40	1581.40	1581.40	1581.40	1581.40	1581.40	4047.63
PNSWS-PV	0.516	0.516	0.516	0.516	0.516	0.516	0.516	0.516	0.592
FNSWS-PV	18.507	18.507	18.507	18.507	18.507	18.507	18.507	18.507	37.967
ENSWS-FC	8850.75	8850.75	8850.75	8850.75	8850.75	8850.75	8850.75	17722.26	8850.75
ENSWM-FC	2157.84	2157.84	2157.84	2157.84	2157.84	2157.84	2157.84	4311.36	2157.84
DNSWS-FC	295.025	295.025	295.025	295.025	295.025	295.030	295.095	581.017	295.025
PNSWS-FC	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.24	30.0
FNSWS-FC	5.587	5.587	5.587	5.587	5.587	5.587	5.587	10.558	5.587
ENSWS-MT	8761.50	8761.50	8761.50	8761.50	8761.50	8761.50	18070.38	8761.50	8761.50
ENSWM-MT	2160.0	2160.0	2160.0	2160.0	2160.0	2160.0	4311.36	2160.0	2160.0
DNSWS-MT	292.05	292.05	292.05	292.05	292.05	292.05	592.35	292.05	292.05
PNSWS-MT	30.0	30.0	30.0	30.0	30.0	30.0	30.24	30.0	30.0
FNSWS-MT	5.373	5.373	5.373	5.373	5.373	5.373	10.636	5.373	5.373
ENSWS-DG	25214.57	25214.57	25214.57	31927.27	30494.54	38242.0	34496.72	34065.50	40582.87
ENSWM-DG	9066.45	9066.45	9066.45	13763.40	11983.32	18455.0	11213.01	11211.04	19456.74
DNSWS-DG	2432.73	2432.73	2432.73	2788.20	3148.50	3104.14	2657.29	2645.39	5064.52
PNSWS-DG	10.363	10.363	10.363	11.448	9.680	12.297	13.021	12.890	7.991
FNSWS-DG	28.302	28.302	28.302	30.361	31.907	31.930	31.457	31.147	41.40
AVSPRES	-	-	-	-	-	-	-	-	-
FWIND	-	-	-	-	-	-	-	-	-
FLOAD	-	-	-	-	-	-	-	-	-
IC	1354.55	1355.06	1366.43	1020.42	1183.38	1125.72	988.13	971.806	902.25
IEARS	1.821	1.821	1.814	1.841	1.810	1.857	1.804	1.80	1.830

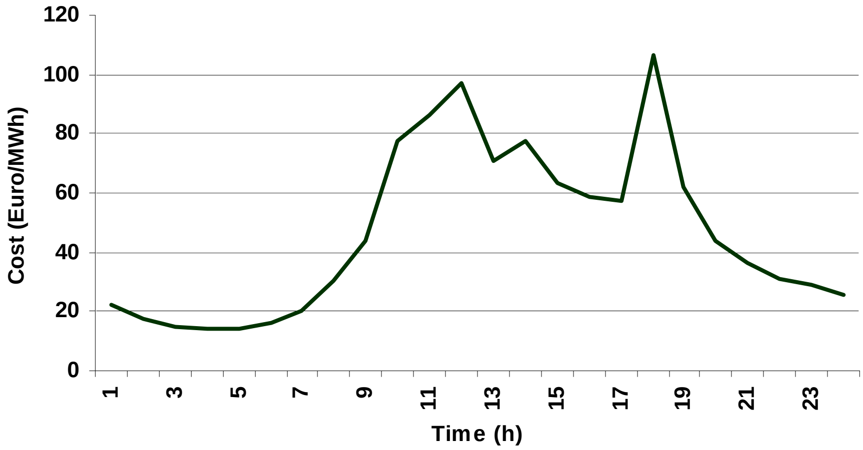

Figure 7: Operating cost function of the system source for one typical day of the year

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

- When the average value for the capacity of the system supply source decreases, the system reliability performance decreases as it is indicated by the respective results for cases 1, 2, and 3. This decrease becomes more significant in case 3. Additionally, the expected energy produced by microturbines and fuel cells increases. The expected energy produced by the renewable energy sources remains the same since it depends only on their technical features and the characteristics of the respective geographical sites at which they are installed.
- The addition of wind generating units always improves the system reliability indices since there is more available power generation to supply the load demand. Furthermore, the energy supplied by wind generating units increases while the energy supplied by the system supply source decreases significantly.
- The addition of photovoltaic units, microturbines and fuel cells improves the system reliability indices, since there is more available power generation to supply the load demand and increases the system generation indices due to the respective sources.
- When a wind penetration margin is applied (case 5), and as its respective level decreases, the expected energy produced by wind generating units decreases and the energy supplied by the system supply source increases significantly. When the capacity of system wind generating units is assumed to increase significantly, Criterion 1 mainly determines the available level of spinning reserve. Additionally, the system reliability performance is affected significantly according to the characteristics of the units as it can be noticed by the comparison of results for cases 1, 4 and 5.
- The use of microturbines and fuel cells provides better reliability and reliability worth indices compared with that when renewable sources are used. However, the system operation cost will increase since the energy supplied by the system supply source increases.
- When the system load demand increases and dispersed generation is installed to cover the increased peak load demand levels, the system reliability performance improves since this generation has a more significant impact on the lower demand levels throughout the year.

Additional results can be obtained for the system nodes which show clearly the impact of the various characteristics concerning the different types of dispersed generation and the interruption costs of system customers. Finally, a greater number of system case studies can be conducted in order to assess better all the system features.

7. CONCLUSIONS

One of the most important aspects of the competitive electrical 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 paper 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 DG sources that can be connected to a distribution system. It also presents the results that were obtained from the reliability assessment studies being conducted for a power distribution system that is based on a typical system with multiple feeders and incorporates various types of dispersed generating units (microgrid). It is shown that the system adequacy is critically dependent on the reliability performance of the system supply source. In addition, the generation capacity of DG sources can improve the system reliability and interruption cost indices. Finally, the obtained results demonstrate clearly the increased information being gained. This is more important for the reliability worth indices that can be used I the economical evaluation of the dispersed generation assessment.

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