Influence of Renewable Energy Sources on Distribution Network Availability

Review

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Abstract *– This paper gives a brief overview of production facilities from renewable energy sources which especially influence the power system with variable production. The paper describes some basic ways of connection and technical data relevant for the design of production plants, as well as the most important influences on the power system, especially with respect to the following: voltage, short circuit current, operation of the system, losses and power quality. Basic concepts of reliability, mathematical models and indicators of reliability are also given.*

Keywords *– availability, connection, impact, reliability, renewables*

1. INTRODUCTION

Basically, all sources of energy in nature come from solar energy. Only a small fraction of solar energy comes to the Earth = 1.5 x 10^9 TWh (30% of this amount is reflected into space, and 70% on the Earth = 1.05 x 10^9 TWh) [1].

Most energy is obtained indirectly in the form of:

- photosynthesis, which represents the chemical energy of plants, and it ultimately gives the internal energy of wood, biomass and fossil fuels,
- evaporation as water and steam circulation in the atmosphere, which gives the potential energy of a watercourse,
- water and air flow, which gives the kinetic energy of ocean currents and wind, and the potential energy of sea waves.

Much less solar energy is used directly as a form of energy.

Manufacturing facilities of electricity from renewable sources including plants with installed power of up to 1 MW that are connected to the distribution network and plants up to 10 MW which can be connected to the transmission or distribution network, include [2]:

1. wind power plants,
2. hydro power plants,
3. solar power plants,
4. geothermal power plants,
5. biofuel power plants (biomass from forestry, agriculture and wood processing industry, biogas from agricultural crops and organic residues and waste from agriculture and food processing industries, as well as waste from industry),
6. fuel cells,
7. power plants using other renewable sources (waves, tides, etc.).

In addition, there follows a classification of cogeneration plants:

1. cogeneration power plants with installed capacity of up to 50 kW, so-called micro-cogeneration units and all cogeneration plants that use fuel cells and hydrogen,
2. cogeneration power plants with installed capacity greater than 50 kW and less than 1 MW, so-called small scale cogeneration units,
3. cogeneration power plants with installed capacity greater than 1 MW and less than 35 MW, so-called medium scale cogeneration units connected to the distribution network,
4. cogeneration power plants with installed capacity greater than 35 MW, so-called large scale cogeneration units and all cogeneration plants connected to the transmission network.

The connection of distributed generation turns a passive unilateral fed distribution network into a doubly-fed active network. The main impacts of sources on such a network are: changes in the network voltage profile, the appearance of transients when turning the sources on and off, an increase in short-circuit currents, the change of losses depending on the production and consumption, congestion of individual lines, the impact on the quality and reliability of supply, the need for coordination of the protection.

The growing demand for safety, reliability and quality of supply puts new weight to planning and development. Inclusion of distributed generation is a challenge itself with respect to issues referring to the quality of supply, stability of the network, system balancing, voltage regulation, protection, failure (isolated mode) and reliability.

A variety of renewable sources is the most important characteristic that defines their work, in terms of uncertainty in predicting the available power, amplitude of changes in power output and the speed of changes.

Stohastic behavior of different energy sources can be represented by Figure 1, similarly to [3].

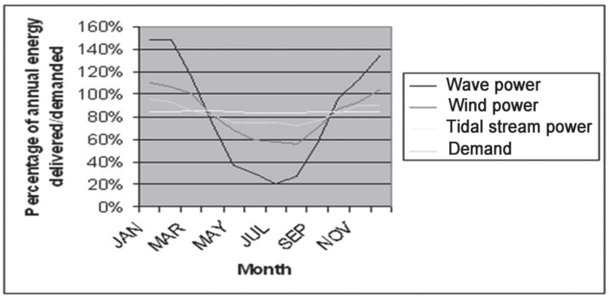

Fig. 1. Percentage of annual electricity generation by wind, wave and tidal power systems occurring during each month, with long-term UK electricity demand distribution shown for comparison (normalized to account for different days per month)

Tidal-cycle variation is given in Figure 2, similarly to [3].

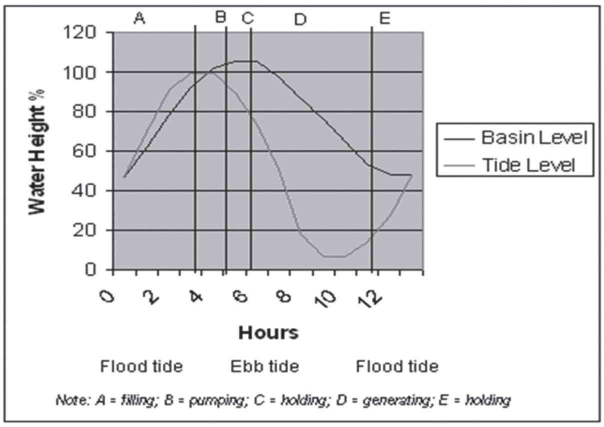

Fig. 2. Tidal-cycle and electricity generation periods for a barrage with additional pumping at high tide

Wind turbine characteristics variation in power output is given in Figure 3.

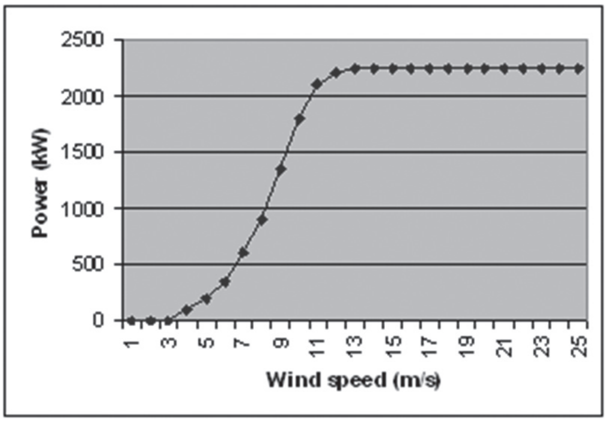

Fig. 3. Wind turbine output characteristics

Water-flow variation is given in Figure 4:

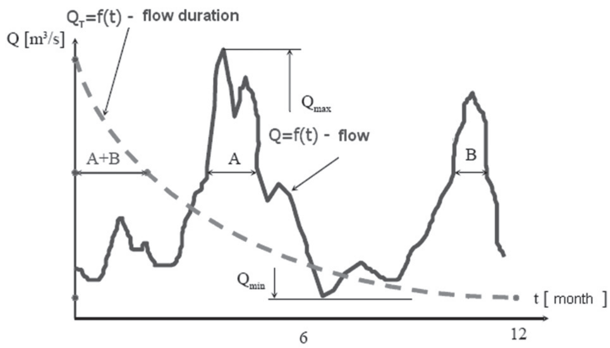

Fig. 4. The curve of the flow and flow duration

A wide variety of technologies and spatial distribution of source locations mitigate the impact of renewable source variability [4]. Variability must be considered in the context of flexibility of the energy system. The impact of changes in the production of renewable sources reduces as the system is more flexible in terms of production (how much capacity with fast response), demand management, network (interconnection with neighboring systems) and reserves. A flexible system can reliably and quickly respond to changing production and consumption. Changes in consumption and production of renewable energy sources are synchronized with the production of conventional sources, because the production must always cover the demand plus losses, including changes in the production of variable sources. That balanced production is "hot reserve" which ensures the stability of the system. A good planning process is important to ensure sufficient spare capacity. Due to inability of dispatch control, distributed sources are assumed as producers of energy that do not contribute to other functions of the electric power system (voltage and frequency control, network security, backup, etc.), which is why all disturbances in the system must be compensated by conventional energy sources.

Large interconnected systems have several mechanisms for balancing the unexpected changes in consumption and production [5]:

- power plants inertia in the form of mechanical inertia of turbine generators, and thermal inertia of kettles, which have small and passive share, but represent the first line of defense,
- frequency-dependent power plants, which currently can change production in response to the change of frequency,
- backup power plants: pumping-storage power plants in a "hot site" and spare power plants,
- voltage changes in the form of reduced voltage for reduced production.

Increased integration of variable sources increases the need for reserves. The total capacity available in the network must always exceed the peak demand, and this surplus capacity is essential for long term reliable operation of the network. The inclusion of renewable (variable) energy sources leads to that the amount of capacity of conventional sources may be reduced or remain the same. It is important for the security of supply to be maintained at the same level.

2. CONNECTION CONDITIONS

Connection of small power plant (distributed sources) to the distribution network may be at low voltage level (0.4 kV) and at medium level (10, 20, 30, 35 kV), depending on the total power of the power plant, the nominal power of the generator, the circumstances of the distribution network , the power plants operation mode and other factors.

Connection to:

1. a low-voltage network:
   - a power plant up to 500 kW - at the low voltage line or low voltage buses of 10 (20) / 0.4 kV substation,
   - a power plant up to 100 kW - at the low voltage line.
2. a medium-voltage network (10, 20, 30, 35 kV):
   - a power plant up to 1000 kW - at the medium voltage line,
   - a power plant over 1000 kW - at the medium voltage line, input-output system.

A possible way of connecting the power plant to the distribution network is determined by a detailed techno-economic analysis to define the optimal solution in terms of connection costs and the impact of production facilities on the distribution system. The final evaluation of the capabilities and mode of connection of distributed sources to the distribution network has been adopted with regard to the state and expected development of the distribution network, and after calculation of voltage drops, load flow, short circuit current and total harmonic voltage distortion.

Defining the conditions for connection to the distribution network ensures reliability of the electric power system and user facility, and avoids at the same time unacceptable detrimental effects between them. Technical requirements for connection of generating units to the distribution network are delivered by the distribution system operator. The Grid System Rules define the basic features at the connection point to the distribution network and general requirements for the connection of system users to the distribution system, as well as special conditions to be met by all generating units connected to the distribution system under normal operating conditions.

The distribution system operator defines the basic technical information relevant to the design of manufacturing plants:

- available capacity,
- data for insulation coordination,
- concept of protection (fault clearance time in the user's facility with the primary and backup protection),
- maximum and minimum short circuit power,
- terms of parallel operating with electric power systems,
- the share of higher harmonics and flickers towards the principles for determining the effect on the system,
- breaking capacity for the corresponding nominal voltage of the transmission network,
- way of earthing,
- maximum and minimum continuous operating voltage, the duration and level of short-term overdraft,
- typical load profiles,
- nature and extent of reactive power exchange, and installed reactive power reserve into the user's facility, for the production and delivery of energy, power plant must generate a sufficient quantity of reactive power. Production of reactive power should be in the range of cos $\varphi = 0.85$ inductively to cos $\varphi = 1$, except for solar power plants, where such a claim does not arise, and wind farms with asynchronous generators for which it is expressed in additional terms of Grid System Rules,
- stake in the plan of the defense system (underfrequency load shedding, undervoltage shedding, manual and automatic control),

- share in securing ancillary services,
- behavior in large-scale disturbances (the ability to pass through a state of failure),
- the method of measurement and calculation,
- integration into the remote control system,
- integration into the telecommunication system.

3. INFLUENCES ON THE ELECTRICITY SYSTEM

Responsibility for safety and reliability of the system is assigned exclusively to the operator of the system, which takes care about maintaining the system frequency, voltage control and reactive power exchange and restores power supply in case of failures. Connecting a large number of new distributed sources, particularly wind power plants, on the system increases significantly the need for additional system services (such as e.g. the regulation of active power and frequency and reactive power and voltage), so that the allowed power of wind power plants, which can be connected to the transmission and distribution network in the Croatian power system is currently limited to 360 MW, mainly determined by the regulatory capacities of existing plants within the power system [6].

Increasing the number of power plants capable of providing support services would contribute to greater possibilities of "equalization" variable wind power generation. Support services are secondary and tertiary control, production of reactive power, ability for isolated power plant operation, willingness to work on its own consumption, readiness for immediate start [7].

Basic technical requirements for connecting distributed sources to the distribution network (given in the Grid System Rules [2] and the standards EN 50160, EN 61000 standards and HEP bulletin number 66 [8]), define the main influences on the system:

- Frequency deviation
  The nominal frequency of the Croatian electric power system is 50.00 Hz, the frequency tolerance in normal operation is ± 50 MHz, while the temporary stationary state is ± 180 MHz. Currently, deviation from the nominal value shall not exceed ± 800 MHz.
- Voltage deviation

  The permissible deviation from the nominal voltage is:

  * For low voltage (0.4 kV): over a period of one week, 95% of a 10-minute average effective voltage should be in the range ± 10% Vn. All 10-minute averages of effective voltage should be within the range of Vn +10% / -15%.
  * For medium voltage (10 kV, 20 kV, 30 kV and 35 kV) over a period of one week, 95% of 10-minute average effective voltage should be in the range of ± 10% Un.
- Voltage waveform

  The factor of total harmonic voltage distortion (THD) caused by the connection of power plants at the connection point to the network must not exceed for voltage level of 0.4 kV: 2.5% for 10 and 20 kV: 2.0%, and for 30 and 35 kV: 1.5%. These values refer to 95% of the 10-minute average effective voltage for a period of one week.
  The flicker values caused by the connection of power plants at the connection point to the network must not exceed 0.7 for short flickers and 0.5 for longer flickers.
- Voltage asymmetry

  Voltage asymmetry in the takeover place caused by a producer of electricity shall not exceed 1.3% of nominal voltage at 95% of the 10-minute average effective voltage for a period of one week.
- Operating and protective grounding

  The owner of the plant should ground its facility and installations in accordance with technical regulations and standards. They should take into consideration the conditions arising from the earthing method of the neutral point of the distribution network to which it connects.
- Short-circuit level

  The plant connected to the network must be designed such that it can withstand the short circuit currents without damage. Information on the expected short circuit currents provides the distribution system operator in order to properly design equipment.
- Levels of insulation

  Isolation of equipment in the plant must be designed in accordance with the voltage level at which it joins. Insulation levels of equipment at a voltage of 10 kV must meet the level of insulation of 20 kV for a possible transition to a higher voltage level.
- Protection against faults and malfunctions

  Protection of sources must be consistent with adequate protection in the distribution system so that failures on the manufacturer's plant will not cause disruptions in the distribution system or with other network users. It is important to set the time of break in supply and achieve selectivity.
- Power factor

  Distributed source should also generate and deliver reactive energy, to within the range 0-75% of produced energy, which corresponds to a power factor of 1 to 0.8 capacitive, depending on voltage conditions on the buses distributed source and loads in the network. If the power plant, due to the transmission system operator, is required to deliver power to the power factor cosφ <0.95 (inductive or capacitive), it has a right to compensate expenses due to increased losses (I^2R).

3.1. EFFECTS ON VOLTAGE

Connection of new electricity producers changing conditions in the distribution network usually results in relief of the distribution network. If the installed capacity of power plants in a specific area is less than the amount of the load in this area, it can be generally considered that the power plant has a positive effect on the power situation in the distribution network. If the current capacity of power plants connected to a particular distribution network exceeds the load in this area, a return of power from the distribution network to the transmission network can be expected. The distribution network becomes active, which often increases investments in the network in order to enable the connection of plants to the distribution network. It also leads to increased power flows in the network, reversing the direction of energy towards higher voltage levels and increased losses in that part of the distribution network.

The distribution network is of the radial structure. Simplified, it is powered from substations HV/MV, from which lines radially feed the consumers, hence the switching equipment, protection and management adapted to the practice of a radial one-way flow of power.

Connection of the power plant to the distribution network (the example is given in Figure 5, similarly to [10]) led to a change in power flows in the distribution network, which among other things, change voltage conditions in the distribution network [9].

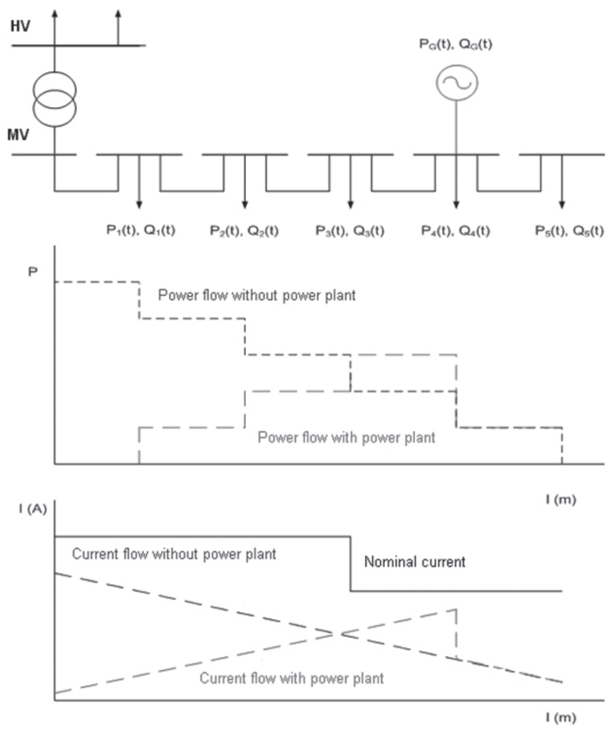

Fig. 5. Example of power plant connection on the radial line

3.2 EFFECTS ON SHORT CIRCUIT CURRENTS

The most common failures in the power system are short circuits. Considering the type, they are rated from single-pole to double-pole and three-pole short circuits with low impedance to the fault location. Predicting short circuit currents is important because of possible damage equipment due to excessive short circuit currents, as well as the settings of protective devices to detect the minimum short circuit. The results of the analysis of short circuit are used for access to the necessary level of switching power of individual switches that must be greater than the maximum short circuit power. In addition to sizing of equipment, this analysis is carried out in order to examine the rigidity of the network at the connection point of the plant.

There are three values of the short circuit current relevant to the choice of equipment in a power system regardless of which type of short-circuiting is least favorable:

1. impact short circuit current (maximum value of short circuit current from the moment of its creation, it is essential for determining the maximum dynamic stress of network elements),
2. switching short circuit current (effective value of the of short circuit current flowing through the switch at the time of the separation of its contacts), and
3. current relevant to warming in the duration of short circuit current (effective value of the short circuit current at the time of occurrence of a short circuit until the interruption of short circuit).

The influence of power plant aggregate on the level of short circuit in the network depends on its performance. The existence of distributed generation units which have directly connected synchronous or asynchronous generators in the distribution network affect an increase in short circuit current, and thus short-circuit power.

During construction of a distribution network including distributed sources it is necessary in some cases to replace switching elements due to increased levels of short circuit current. For the distribution network short-circuit power is maximum usually in the HV/MV transformer node. In case of power plant connection, it is necessary to check the short circuit power in each case of the connection, and if deemed necessary to keep its amount within the acceptable range by using appropriate measures within the plant.

3.3 EFFECTS ON OPERATION MANAGEMENT

The current operating practices, control switchgear, voltage regulation and protection of the distribution network are carried out in accordance with the distribution network constructed for a one-way flow of power from high-voltage substations toward consumers at the medium and low voltage.

At the point of connection to the distribution network a switch is installed to separate the power station from parallel operation with the distribution network due to security reasons. Switch control is local and may be remote. A particular problem is the danger of asynchronous switching on the power distribution network. Therefore, mutual lock of disconnecting switches with other switching devices of the plant prevents asynchronous connection to the distribution network. In the distribution network, but also in the power plant, it is necessary to ensure the conditions (blocking) that during the execution of automatic restarting cannot get to asynchronous restarting. The generator circuit breaker is a usual place of the synchronization generator plant.

For operating the distribution system, the distribution center must have available data on how the power plant operates, on supplies/acquisitions of electricity to/from the network, on the position of disconnecting switches and the implementation of safety earthing and short circuiting. The distribution system operator leads the system operation so as to enable undisturbed delivery of electricity from power plants. It is authorized in any danger or malfunction, disconnecting the switch for the separation, to separate power plant from parallel operation with the distribution system. The restoration of parallel operation should occur only when all requirements for a safe and reliable operation are fulfilled.

3.4 EFFECTS ON POWER QUALITY

Power quality is a characteristic of electricity at a certain point of the power system and it is usually considered as continuity of supply (availability of electricity) and voltage quality.

The system operator and system users as well are responsible for the power quality at some point in the network. The system operator limits the negative feedback effect of equipment of all users on a network, a network user (customer, manufacturer or retailer of electricity) is required to limit reverse the effects of their equipment on the voltage quality (harmonics injection, taking reactive power, flicker emission and asymmetry of the load) to define (agreed in advance) the limit values (determined by the system operator).

The power quality at some point in the distribution network is expressed through several parameters [11]:

- voltage frequency,
- level voltage in steady state (usually 10-min RMS averages),
- harmonic distortion of a voltage waveform (a consequence of the operation of the equipment which has a nonlinear V-C characteristic: circuits of power electronics and electric machines, whose magnetic materials enter into saturation, causing higher harmonic currents injected into the network that on the network impedance create voltage drops, causing distortion of the waveform of voltage),
- voltage harmonics,
- fast dynamic voltage changes or flickers (the result of the variability of the intensity of primary energy sources such as wind, manifested as a subjective impression of changes in the intensity of light),
- voltage asymmetry,
- voltage drops,
- network frequency overvoltages,
- transient overvoltages (may occur as a result of switching capacitors, needed for reactive power compensation, taken from a network by asynchronous generators directly connected to the network),
- signal voltage, the network tone frequency management - TFM (plants that use energy converters can transmit disturbances in the form of harmonics in the frequency spectrum close to the frequency of the TFM system and thus cause a false operating of TFM or TFM signal damping in the network).

Equipment connected to the distribution network was designed and built for the nominal voltage Vn sine wave and the nominal frequency of 50 Hz, but it must be resistant to a certain level of interference, which is almost always present in the network (e.g. voltage waveform harmonic distortion). This level of interference is referred to as resistance level at which the equipment is still working properly without losing functionality, rapid aging, damage or destruction. On the other hand, most of the equipment through its work affects the voltage level and waveform (emission of current harmonics, flickers, etc.) and thus introduces disturbances into the network. Therefore, the level of compatibility is defined as the maximum disturbance level at which the equipment of different users of the network operates satisfactorily. The compatibility level must therefore be less than or equal to the resistance level of equipment connected to the network.

<u>Hydroelectric power plants</u>

Hydropower plants do not have marked oscillations of the drive moment of the machine. Hydropower plants with a synchronous generator can significantly affect the amount of voltage in steady state (injection of produced electricity in the distribution network). Sometimes it can affect the distortion of the voltage waveform, while the impact of this type of hydroelectric power in the flickers, voltage asymmetry and the amount of TFM signals can normally be ignored. Because of the possibility of regulating the reactive power, it can positively affect the state of voltage quality of distribution networks. This type of hydropower plants has the ability to work in isolated operation (impact on the frequency of the voltage). A hydropower plant with an induction generator can significantly affect the amount of voltage in steady state, the distortion of the voltage waveform (because of imperfections of the generator), transient overvoltages (concluding capacitor banks) and the amount of the TFM control signal (capacitor banks may become an abyss for the TFM signal).

Photovoltaic cells

Photovoltaic cells directly convert solar energy into direct current, so in this case there is no motor, the mechanical energy source is converted into electrical energy (motion guide in the magnetic field). So you need a power converter (inverter) for coupling the photovoltaic cells on the grid. Through their work photovoltaic cells can significantly affect the amount of voltage in steady state (injection of produced electricity in the distribution network), the distortion of the voltage waveform (the existence of an energy converter), and interference TFM control receivers.

Fuel cells

Impact of fuel cells on voltage quality in the distribution system will in practice be almost identical to a photovoltaic cell. The only difference is in how to obtain direct current the fuel cells obtained by chemical process.

Wind farms

With their work and due to the stochastic nature of wind, wind farms significantly affect voltage conditions at the point of connection to the network, and the impact depends on the type of the applied wind turbine. While wind generators with power converters can automatically perform voltage or power factor in the given limits, so far the impact of a wind turbine with asynchronous generator voltage depends on the X/R ratio of the network. Flickers (variations in the amount of voltage ranging between 0.01 and 10 Hz) result from the variation of the generated power resulting from wind turbulence, and are transferred directly to a network of wind turbines with a constant speed, while wind turbines with power converters eliminate the changes. When connecting a wind turbine with a constant speed to the network, high amounts of electricity cut-downs can cause higher voltage, while conclusion of the condenser with induction generators directly connected to the network creates an electric strike and the corresponding high frequency voltage transients that spread into the network. Injecting harmonic currents into the network is the result of power converters used in wind turbines with variable speed control [12].

3.5. EFFECTS ON LOSSES

The impact of a power plant on losses in the distribution network is difficult to determine, since these losses in the network change by changing the power flow. It is generally considered that distributed generation reduces losses at the system level. Network losses increase when the distributed generation greatly exceeds the amount of load, then when the power factor in the power plant connection point should be arranged by strong inductive character to ensure the existence of acceptable operating conditions in the network (especially the allowed voltage range). Network losses do not represent operational constraints, but they should be minimized.

4. AVAILABILITY / RELIABILITY

4.1. BASICS

Reliability is a mathematical probability of satisfactory operation under certain conditions and during a specified period of time.

Availability is a mathematical probability of satisfactory operation under certain conditions and to a certain time in the future.

Electric Power System (EPS) is a collection of interconnected power stations, networks, and consumers whose primary function is to ensure production, conversion and transmission of electric energy to consumers. Reliability of the electricity system is defined as the probability that the system is capable of delivering electricity to consumers in a given time period with an acceptable operating condition (rated power, voltage and frequency within tolerable limits).

Reliable electricity supply of customers in the open electricity market is one of the most important items in the quality of electricity supply. According to most of the world statistics of operating events, 80-90% of all interruptions occur just in a distribution system, and the greatest responsibility for the reliability of supply is on the distribution system operator. Away from a vertically integrated power system, reliability becomes a binding element of network operators in the new legislative provisions, and thus an integral part of planning and evaluation of the distribution system.

There are three main aspects of reliability:

- Sufficiency: the ability of the power system to supply the consumers with electric power and energy of the nominal values of load and voltage limits, taking into account planned and forced outages in the work of individual components in the system. With regard to the situation observed sufficiently long after the disturbance in the system, this term is also called static reliability.
- Security: the ability of the power system to withstand sudden disturbances in unexpected outages of components, where the transient period after the disturbance is observed and it is often called dynamic reliability.

- Integrity: the ability of the power system to maintain satisfactory working conditions when working in the interconnection with other power systems.

Reliability analysis of power systems is always referred to as interruption of the consumer supply. Various mathematical models allow evaluation of system reliability, calculating indicators of reliability

4.2 MODELING SYSTEM FOR ANALYZING

Techniques for quantitative assessment of reliability of electricity systems include modeling system for computer processing of data collected. The most common approach to calculation of reliability are Markov processes considering the electric power system as a system with a dependent, repairing components and reserves. Markov processes are a type of Markov models that are functions of two random variables: discrete states of the system and continuous time of observation [13,14].

Generally, operating states of the distribution network can be modeled with the model of four states [15], as in Figure 6:

- state "0" – normal operating state of the system, without failure, all consumers are normally powered,
- state "1" – state of the system with transient malfunction, switch turns off the protection, automatic reclosing (AR) is a success,
- state "2" – state overlaps with a permanent failure in which the unsuccessful AR switch turns off part of a network, in which customers remain without power and establish a state "3", a so- called state of the reserve power,
- state "3" – state of repair for a permanent failure, only part of the network with failure element is turned off and consumers of this part are without power, while the others are backup powered.

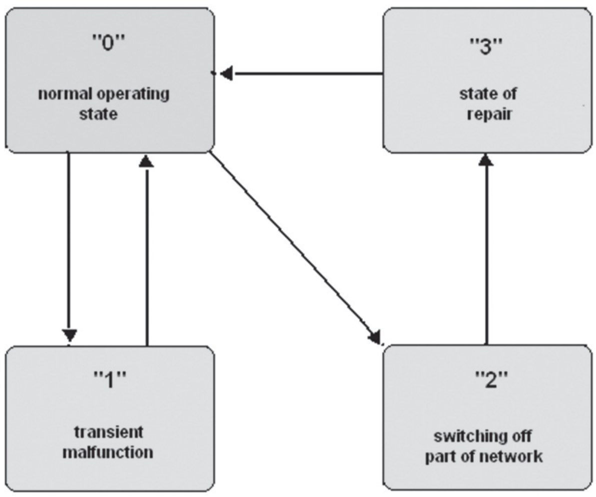

Fig. 6. Model of the four states

From state "1", the system automatically returns to "0", while from state "2" after switching revert to "3", and out of it after the repair exceeds state "0".

Elements of the model for reliability calculation are actually branches of a distribution network that is necessary to establish information about faults trees and switching appliances on the branches. These statistical data are collected by monitoring the behavior of elements in a given period of time.

The data needed for modeling are:

- data on permanent faults of branches (frequency of permanent faults, time overlap for permanent failure, repair time for a permanent failure),
- data on transient faults of branches (frequency of transient failures, restarting time),
- information on switching equipment and protective devices in the branches,
- basic data on the network - the topological structure, the load on the nodes, allowable load current and impedance of network elements.

All the described conditions are calculated in the model of network by simulating failures (on all branches) which cause interruptions nodes, based on the basic input data about the topology and input data on the reliability of system parts (frequency of branches failures, times for individual states). In this way, reliability indices are calculated from the failure rate of branches for all network nodes; these indicators represent the indicators of reliability of customer supply in such nodes.

Reliability indices are generally:

- frequency of the transient interruption of nodes [interruption/year],
- frequency of permanent interruption of nodes [interruption/year],
- frequency of total interruption of nodes [interruption/year],
- annual duration of the transient interruption of nodes [h/year],
- annual duration of the interruption of nodes due to state "2" [h/year],
- annual duration of interruptions of nodes due to state "3" [h/year],
- annual duration of permanent interruptions of nodes [h/year],
- total annual duration of interruptions of nodes [h/year],
- average duration of permanent interruptions of nodes [h/interruption],
- expected annual undelivered electricity in the system [MWh/year],
- the annual cost of undelivered electricity in the system [€].

When calculating reliability of the system including generating units, particularly for renewable energy sources whose work is heavily dependent on weather conditions, ambient conditions, and atmospheric effects are additionally modeled (e.g. state of calm and stormy weather).

4.3 INDICATORS OF RELIABILITY

The terms used for defining reliability indices are [16]:

- Interruption - termination of a power supply of one or more customers connected to the distribution part of the power system. It is the consequence of the interruption of one or more components, depending on network configuration.
- Forced outage - state of component not able to function because of unplanned events directly associated with this component.
- Planned outage - the loss of electric energy that occurs when a component is deliberately switched off at the chosen time, mostly due to preventive maintenance, reconstruction or repair.
- Duration of the interruptions - period from the beginning of interruption of the electricity supply of a customer to return of power supply to the customer. According to the duration of the interruption, it can be short-term and long-term. According to the European standard 50160, short interruptions last up to 3 minutes, otherwise they are long.

Reliability indicators can be oriented toward the consumer (SAIFI, SAIDI, CAIFI, CAIDI, ASAI) or toward the load and energy (ENS, AENS) [17, 18].

The frequency of interruption customer j is approximately equal to the sum of the failure rate of all components to the customer:

$$f_j \approx \lambda_s = \sum_i \lambda_i [interruption/year], \quad (1)$$

where:

- λ_i – component i failure rate.

Unavailability due to interruption of supply of customer j is the sum over the failure rate and duration of interruptions:

$$N_j = N_s \approx \sum_i \lambda_i \cdot r_i [h/year], \quad (2)$$

where:
- λ_i – component i failure rate,
- r_i – duration of interruption of component i.

Mean duration of interruption of supply of customer j is the quotient of unavailability and customer failure rate:

$$r_j = r_s \approx \frac{N_s}{\lambda_s} = \frac{\sum_i \lambda_i \cdot r_i}{\sum_i \lambda_i} = [h/interruption], \quad (3)$$

where:
- λ_i – component i failure rate,
- r_i – duration of interruption of component i.

System Average Interruption Frequency Index (SAIFI) shows how many interruptions an average customer will experience in one year, which is given by the following expression:

$$SAIFI = \frac{total\ numbers\ of\ interruptions}{total\ number\ of\ customers}, \quad (4)$$

or:

$$SAIFI = \frac{\sum_j \lambda_j \cdot n_j}{\sum_j n_j} [interruption/year] \quad (5)$$

where:

λ_j – frequency of interruptions of supply customers in node j,

n_j – number of customers in node j,

$\sum_j n_j$ - total number of customers in the system.

System Average Interruption Duration Index (SAIDI) indicates the total duration of interruptions for an average customer through a certain period of time. It is calculated by using the following equation:

$$SAIDI = \frac{total\ duration\ of\ interruptions}{total\ number\ of\ customers} \quad (6)$$

or:

$$SAIDI = \frac{\sum_j N_j \cdot n_j}{\sum_j n_j} [h/year] \quad (7)$$

where:

N_j – unavailability of customers in node j,

n_j – number of customers in node j,

$\sum_j n_j$ - total number of customers in the system.

Customer Average Interruption Frequency Index (CAIFI) shows the number of interruptions of each customer in one year. It is calculated by using the following equation:

$$CAIFI = \frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ affected\ customers} \quad (8)$$

or:

$$CAIFI = \frac{\sum_j \lambda_j \cdot n_j}{\sum_j n_j} [interruption/year], \quad (9)$$

where:

λ_j – frequency of interruptions of supply customers in node j,

n_j – number of customers in node j,

$\sum_j n_j$ - total number of customers in the system.

Customer Average Interruption Duration Index (CAIDI) shows the average annual duration of one interruption of a customer. It is calculated by using the following equation:

$$CAIDI = \frac{total\ duration\ of\ customer\ interruptions}{total\ number\ of\ customer\ interruptions} \tag{10}$$

or:

$$CAIDI = \frac{\sum_j N_j \cdot n_j}{\sum_j \lambda_j \cdot n_j} = \frac{SAIDI}{SAIFI}[h/interruption] \tag{11}$$

Average Service Availability Index (ASAI) is shown by the following expression:

$$ASAI = \frac{available\ hours\ of\ customers\ supply}{required\ hours\ of\ customers\ supply} \tag{12}$$

or:

$$ASAI = \frac{\sum_j N_j \cdot 8760 - \sum_j N_j \cdot n_j}{\sum_j N_j \cdot 8760}[\%] \tag{13}$$

Average Service Unavailability Index (ASUI) is shown by the following expression:

$$ASUI = 1 - ASAI[\%] \tag{14}$$

Average Energy Not Suplied Index (AENS) is shown by the following expression:

$$AENS = \frac{total\ energy\ not\ served}{total\ number\ of\ customers} \tag{15}$$

4.4 INFLUENCE OF RENEWABLE ENERGY SOURCES ON RELIABILITY / AVAILABILITY

With regard to the application of distributed sources and stochastic dependence of their power output there are particularly important aspects of the following uncertainties:

a. Predicting the load / generation

b. Inserting production units in the production schedule is carried out on the basis of previous load forecasting that includes uncertainty in the range of 3%. Increasing the share of uncontrollable units marked by a stochastic behavior increases uncertainty of load forecasting and production.

c. Customizing requirements with regard to capacity reserves and installed capacity

d. Nowadays, the demands with regard to capacity reserves (primary and secondary) are based on the principles of traditional vertically integrated energy systems with large numbers of conventional sources and a smaller number of uncontrollable units. Fluctuations and outages of production units affect reserve capacity, a total installed capacity has to be reviewed with regard to reliability, because the distributed sources replace only one part of it.

e. Transmission network planning

f. When planning a high-voltage transmission network, distributed sources may represent an alternative to standard solutions of network development. Availability may be time dependent and related to the current state of the load and may become subject to planning. With distributed generation unavailability for distributed units is significantly higher than that of lines, and the n-1 rule is not enough.

g. Distribution network planning (MV and LV)

h. Uncertainty in the construction and location of distributed resources affects the distribution network, which has to be used more efficiently in new circumstances. The impact of distributed resources on power flows in distribution networks is necessary for accurate calculation, for better planning, in order to avoid or delay additional investments in the network.

Power plants that use solar energy, wind and water, belong to the category of plants whose production cannot plan because of what it is even more complicated to run the power system with a significant proportion of this type of power plants. Although they use a free primary energy source, power plants with varying production do not have the possibility of storing energy, and unpredictable weather conditions affect their work. Therefore, the main potential problem of massive introduction plants with varying production in the distribution network is an increased need for control power [19].

Additionally, if the integrated power plants are outside the system of hierarchical leadership from the highest center, and with the absence of the ability to track the load curve, they do not significantly affect reliability of supply. For such sources, fluctuations in power output are added to fluctuations caused by changing loads. Power plant inclusion in the production schedule is carried out on the basis of previously derived predictions of the load. Forecasting production depending on the technology of distributed sources should be introduced for the analysis of implementation of uncontrollable units. If they are involved in an integrated system of managing the electric power system, distributed sources can have a positive impact on the system in the form of increased reliability. The aspect of reliability is more significant for consumers connected to the distribution network than the system as a whole. Generally, reliability of power supply usually does not increase the integration of distributed energy sources that are outside the distribution network control. In addition, it is necessary to act preventively such that distributed sources do not affect reliability of supply for reasons such as a non-selective system of protection, auto re-inclusion, etc.

Positive effects of the power plants connection on availability of the distribution network are:

- isolated power plants operation with their own consumption and / or isolated operation with a part of the distribution system (if permitted),
- relief distribution network elements (e.g. lines or transformers) in the event of failure or unavailability of certain elements of the network allow undisturbed supply of all or part of the network for consumers supplied from distributed generation.

Negative effects of power plant connection on availability of the distribution network are:

- an increased risk that the failure at the plant causes the disturbance in the distribution system,
- additional requirements for fault protection, and the possibility of non-selective tripping of protection in case of the failure at the plant,
- increasing short circuit currents in a distribution network that reduce switching equipment lifetime,
- increased duration of energy not supplied in the case of an outage.

After defining the optimal solution in terms of power conditions in the network in normal operation, the analysis of reliability of electricity supply to consumers is carried out. One approach is the principle (based on the Grid System Rules) that any investment in reliability of supply must be economically justified by reducing the cost of energy not served (and possibly loss of energy and power). The second approach provides an auxiliary supply of specific consumers or consumer groups (e.g. 10 kV feeders or the 35/10 kV substation) in the event of unavailability of a network element (called an "n-1" reliability criterion). The third approach to reliability analysis is to define the exact indicators of the quality of electricity supply to consumers and the values of these parameters that must be achieved in some parts of the network [20].

System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are used as a measure of the availability of supply of electricity. The influence of the connection of a distributed source on these indexes is primarily related to the way of connection to the network, where there are two characteristic cases:

1. A small power plant that has the possibility of isolated operation, power supply part of the distribution network in case of an outage of the feeder to which it is connected (under the condition of power/frequency control and power management) has a positive effect on indexes because it can ensure availability of the power supply, i.e. the part of a distribution network that would otherwise remain without power.
2. A small power plant that is connected to an existing distribution network via a new radial feeder or lateral by the system input-output, with the increased overall length of the network, negatively affects the indexes of availability because it will increase the duration of the interruption, approximately the amount ratio of the length part of the new network and the total length of existing feeders with lateral lines due to the increasing probability of malfunction.

5. CONCLUSIONS

The technological development of small production units and subsidies related to the production of electricity from renewable energy sources, as well as liberalization and opening of the electricity market, have stimulated an increased use of renewable energy sources. Inclusion of renewable energy sources, such as distributed generation, changes the current function of the distribution network, which becomes versatile powered, which takes over the role of the transmission network. In this environment, the requirements on safety and availability (reliability) of the system (distribution network), are becoming even more evident due to changing ownership relations and the requirement for maximum economic benefit. Large losses in transmission are an additional factor promoting the development of local - distributed generation close to consumption.

To facilitate the introduction of renewable energy source there is a need for fundamental changes in technical, economic and regulatory aspects related to networks that play the key role in their integration into the system, given the significant investments needed to build the source, but also to enhance and build networks. In light of new ideas, in order to reduce costs, additional investment may be replaced by measurements, coordinated control of voltage and generally wide system monitoring in real time.

The quality of electricity supply from the standpoint of consumers describes various indicators on the number and duration of power interruptions. However, it takes a lot of precise information on operating events over a period of many years for the estimation of the current quality of electricity supply to consumers, especially for planning future network development, it is sufficient to use data on the number of customers connected by each 10(20)/0.4 kV substation (a good estimate is the average number of consumers by 1 kVA embedded in the transformation of 10(20)/0.4 kV substation), the type of interruption of electricity supply in terms of duration (long, short, very short), frequency of interruptions, duration of interruptions and objectives of the quality of supply (commonly SAIFI and SAIDI).

Reliable customer power supply in the open electricity market is important from the perspective of the quality of electricity supply. In planning development it is necessary to consider reliability indicators to define different variants of development, and determine the optimal level of reliability at low cost. Reliability calculation methods for planning a network are determined by the current and future levels of reliability, taking into account the changes of network parameters (topological, energy, etc.). Due to comprehensiveness and complexity, calculation of reliability itself is a long and expensive process.

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