A logical-probabilistic model for analysing the reliability of wind – diesel generator autonomous hybrid power system

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***Abstract*— A wind-diesel hybrid system involves two generating sources, diesel generators and wind turbines. They are designed to increase the capacity and reduce the cost and environmental impact of generating electricity in remote locations that are not connected to the electricity grid. Wind-diesel hybrid systems reduce dependence on diesel fuel, which creates pollution and is expensive to transport. A paper, a logic-probabilistic model based on a fault tree is developed to analyze the reliability of an autonomous complex system (wind-diesel plant) taking into account the characteristics of generating sources and operating conditions. A calculation of the reliability of a hybrid plant located in the south-eastern part of Bulgaria was made.**

***Keywords*— wind-diesel hybrid system, wind turbines, fault tree, reliability, logic-probabilistic model**

I. Introduction

All types of engineering systems frequently fail in the realm of engineering. Different failures might have various effects. Numerous causes, including flawed design, subpar components, poor maintenance, age, wear and tear, and human factors, contribute to failures. Investigating probable causes of failure is the first stage in reliability analysis, and the creation of the system's reliability model is the reliability analysis's most difficult task [1]. The most popular methods for creating reliability models are reliability block diagrams, models, and fault tree analysis [2, 3]. Fault Tree Analysis (FTA) is widely used for dependability evaluation and decision-making process of a wide range of systems by reliability block diagram to represent the logical relationships in a system [1, 4, 5]. Chiacchio et al presented a new method for estimating the amount of energy produced in a solar power plant by stochastic hybrid fault tree [6]. In a hybrid system based on renewable energy sources, all these established stochastic models may be used to estimate future real power output [7, 8]. The major objective is to reduce the cost of the power outage in the distribution system while meeting the needs of the system. Through effective optimization, the effects of renewable energy sources on the reliability of a power system may be evaluated [9].

Titova et al [10] proposed reliability investigation of two wind turbines and solar energy sources based on state graphs. In the paper are compared different types of chosen scheme according to technical and economic data.

Because it can study associated dependability and estimate reliability, the fault tree analysis approach was used. The system is separated into fault trees for each component in this study to display the faults that could damage that component.

The system is represented by the fault tree in this study, with all of its constituents serving as inputs to signal the probability of power failure.

It is commonly known that the fault tree approach may be used to successfully simulate the likelihood that a system will fail based on the likelihood that individual components would fail. Through fault tree analysis, it is possible to pinpoint the root cause of a breakdown and determine how reliable a system is. The fault tree enables one to ascertain the operational relationships between various components under various operating modes and to create analytical expressions for failure probability.

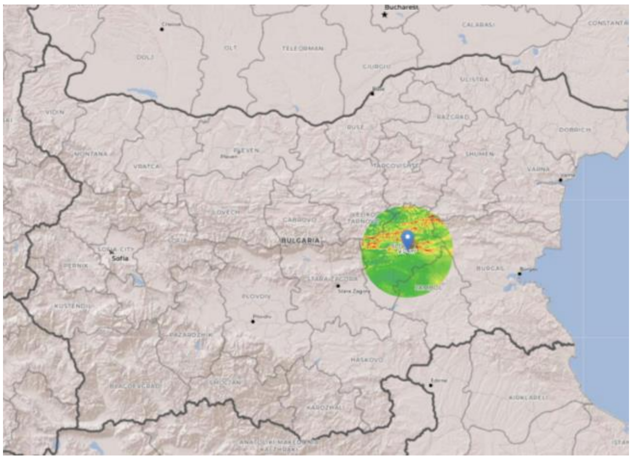

Fig. 1. Map of Sliven region in Bulgaria including buffer area of 50 km – Latitude: 42.69°N, Longitude: 26.33°E, Elevation: 271m.

Wind and solar energy are available in many places of Bulgaria, particularly the south-west region. Gospodinova et al demonstrate in their study, using a variety of modelling studies, that the location of Sliven is extremely advantageous for the use of wind generators in the generation of electrical energy [11]. The Sliven area, located in southeastern region in Bulgaria was chosen to showcase the developed approach since the facts therein are sufficient, Fig. 1. Weather data is an important input for the feasibility evaluation of a renewable hybrid energy system. The wind energy resources statistics come from a database for the Bulgarian city of Sliven [12, 13].

According to [12] the presented yearly bar-chart clearly demonstrates a consistent trend of increasing wind speed throughout time, Fig. 2.

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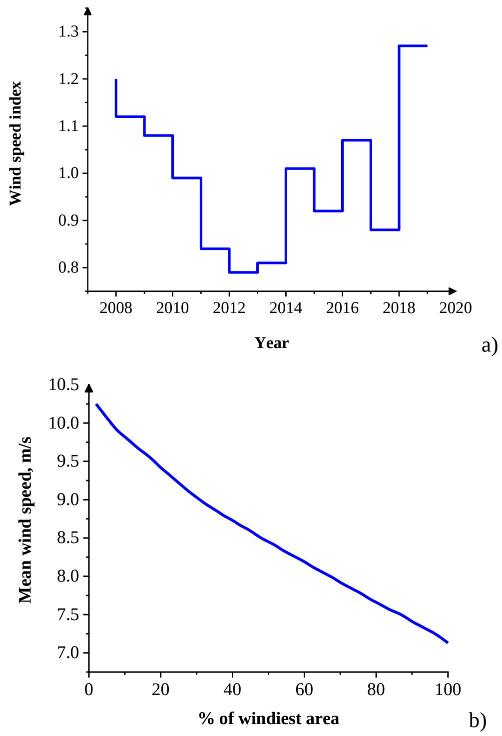


Fig. 2. Wind parameters for the Sliven area in Bulgaria: a) wind speed variability annual barchar; b) mean index value as a function of the percentage of windiest area [2].

The goal of this work is to create a methodology for performing a reliability analysis of an off-grid wind-diesel hybrid power system while accounting for the stochastic nature of wind speed. The article considers the failure sequence of the components that comprise the overall hybrid generating system. The architecture of the investigated system includes two generating power sources: a diesel generator and a wind turbine, as illustrated in Fig. 3. The use of batteries in the power system is required to smooth out any fluctuations in wind turbine power due to the unpredictable nature of wind speed.

It is well known that lithium technology has the best mass-energy density ratio. According to various literary sources, the following drawbacks of utilizing lithium-ion batteries exist: loss of capacity at high temperatures; loss of capacity during charging; need for a voltage and current protection scheme; high probability of electrolyte leaking in case of battery integrity violation [14–17]. It is obvious that all of these circumstances can result in battery failure.

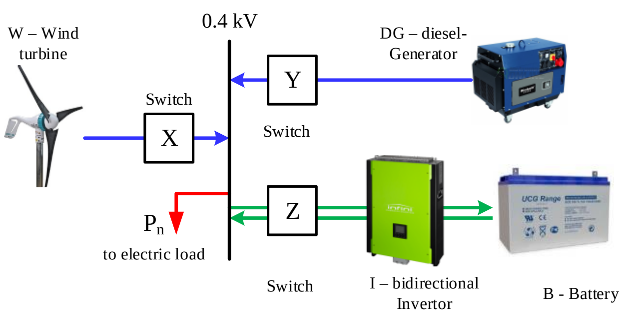


Fig. 3. Structure scheme of off-grid wind-diesel hybrid power system: W - wind generator; G- diesel generator; I - system invertor, B - battery, Pn - electric power to electric load; X, Y и Z - curcit breakers.

II. Methodology

To study the complicated system, the failure tree approach was utilized, which allows for the differentiation of short-term and long-term failures. A fault tree is an acyclic directed graph that contains nodes of two types: events and logical symbols. An event is a phenomena that occurs inside the system, most commonly a failure of a single component of a subsystem. To describe the propagation of faults in the system under consideration, logical symbols are utilized. One output and one or more inputs are provided in every logic symbol.

There are several approaches for predicting reliability, but fault tree analysis gives a diagrammatic depiction of system dependability. As failure tree analysis gives a static representation of the combinations of failures and consequences that might lead to the occurrence of the defined critical failure, the purpose is to determine the probability of an event of the stated critical failure.

It should be noted that the fault tree is not a representation of all conceivable system defects or causes of system failure. This method is appropriate for analysing a major event, and the fault tree only includes defects that contribute to the major event. It's also important to remember that a fault tree isn't a quantitative model [3].

The failure tree method considers simple and complex events that lead to the failure of a wind-diesel power plant, such as: the failure of one element during the emergency repair of another or the failure of one element during the emergency repair of another, as well as the event of a switching device malfunction.

The suggested method takes into account the wind conditions that have an impact on the plant operates. The sign denotes faults due to wind conditions (V).

The wind conditions influencing on the operation of off-grid systems with wind power generation must be included in the reliability analysis. When the fault tree for the Wind-Diesel power system is created, the rated wind speed is:

$$v_{min} < v < v_{max},$$

When a wind power plant supplies electricity that ranges from zero to nominal, and when the installation is not producing energy, the wind speed is unrated [8]:

$$v_{max} \le v; \quad v \le v_{min}.$$

The fault tree clearly depicts all of the relationships required to produce the top eventp Fig. 4. It is also a physical record of the methodical examination of the logic and fundamental factors that led to the top outcome. The fault tree gives a structure for evaluating the top even qualitatively and quantitatively.

The wind-diesel hybrid power system operates under a variety of meteorological situations. As a result, the modelling of meteorological conditions is done by separating trees into multiple distinct fragments.

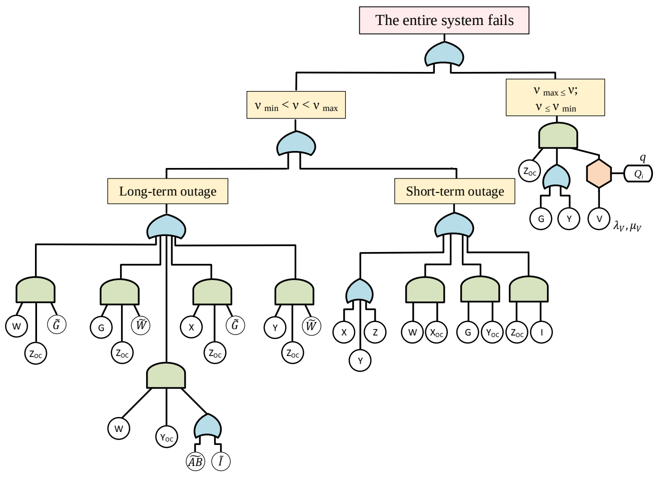
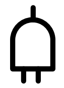
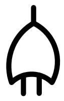
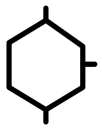
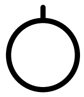
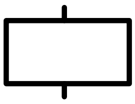


Fig. 4. Fault tree of complex hybrid wind-disel energy system.

The propagation of failures in the system is represented by logical symbols in the fault tree. Each logic symbol contains one or more outputs as well as one input. The following logical symbols are used [18]:

	The "**AND**" element indicates that an output event happens if all input events occur at the same time.
	The "**OR**" element indicates that the output event occurs if any of the input events occurs.
	The input event causes the output to occur, but only if another single event called as a conditional has occurred (for example, a change in wind speed)
	A basic event that occurs at random
	An intermediate event caused by one or more base events

Starting from a lower level, logical functions (LF) are formed by executing logical operations addition ("OR") and multiplication ("AND") on the symbols of the main elementary events and states. As a result, the final event's logical functions will be provided in perfect disjunctive form:

$$\mathrm{LF} = y_i + (y_k * x_{FAILURE\ K}) + (y_i * \tilde{y}_j) + (y_j * \tilde{y}_i) + (y_i * \tilde{y}_j * x_{FAILURE\ K}),$$

where: y_i, y_j, y_k – are elementary events (failures of elements *i*, *j*, *k*); $x_{FAILURE\ K}$ – events that cause switching apparatus, relay protection devices, and automation for the relevant element to fail; *k;* $\tilde{y}_i, \tilde{y}_j$- the state of the elements during an emergency repair.

In the event of a long-term failure, the failure function of the entire power plant takes the following form:

$$F_{\text{long-term outage}} = W\tilde{G}Z_{FAILURE} + G\widetilde{W}Z_{FAILURE} + X\tilde{G}Z_{FAILURE} + Y\widetilde{W}Z_{FAILURE} + W(\widetilde{AB} + \tilde{I})Y_{FAILURE};$$

$$F_{\text{short-term outage}} = X + Y + Z + WX_{FAILURE} + GY_{fAILURE} + IZ_{FILURE};$$

$$F_{system} = (G + Y)VZ_{FAILURE},$$

where *G*, *W*, *AB*, *I* are the plant's elements; $\tilde{G}, \widetilde{W}, \widetilde{AB}, \tilde{I}$ – signifies that the relevant components are in a state of immediate repair; *X*, *Y*, *Z* – switch failure; $X_{FAILURE}$, $Y_{FAILURE}$, $Z_{FAILURE}$ – failure of the system switches when an operation request occurs; V – failure of wind turbines owing to severe wind conditions.

It's well known, operation of wind turbines depends significantly on wind speed. The time when the turbine cannot operate due to extremely high or extremely low values of wind speed (cut-out wind speed) must be known and estimated in order to make the most efficient use of the wind generator. Additionally, the likelihood of these occurrences as well as their potential frequency need to be evaluated. The ability to assess the financial losses incurred during the operation of a wind generator or a wind generator park depends in large part on all of these facts.

For the vicinity of Sliven, Bulgaria, the following wind information is used [12]:

- Cut-out wind speed probability distribution value taken from [13] is: $q = 0.05$;
- Period of the year with cut-out wind speeds is calculated, taking into account the data presented in Meteoblue : $T_0 = 0.61$;
- For the Sliven region in 2021, 142 days with design wind speed were recorded, according to Meteoblue [2]. Time of year with rated wind speed, i.e. when power production no longer varies with wind speed: $T_N = 0.39$;
- The following mathematical expression is used to calculate the frequency of occurrence of cut-out wind speed:

$$\lambda_V = \frac{1}{T_0} = 1.639\ [1/year];$$

- The following statement can simply compute the intensity of restoration to the rated wind speed, i.e. cut-in wind speed:

$$\mu_V = \frac{1}{T_N} = 2.564\ [1/year].$$

According to Gindev [3] the following formula determines the wind turbine cut-off time factor due to bad weather conditions for the investigated year 2021:

$$q_V = \frac{\lambda_V}{\lambda_V + \mu_V}\left[1 - e^{-(\lambda_V + \mu_V)t}\right],$$

$$q_V = 0.384.$$

The following equation describes the likelihood q_V^*, that the wind turbine may malfunction due to weather conditions:

$$q_V^* = q_V q = 0.0192;$$

TABLE I. THE INDICATOR VALUES FOR RELYABILITY OF WIND-DIESEL HYBRID POWER SYSYTEM COMPONENTS [20]

Designation	Component	Indicator value		
		System element's failure rate λ(y), year^{-1}	**Actual time to restore the system element's functionality τ(ỹ), year**	**The system element's state probability q(ỹ)**
W	Wind turbine, 225 kW	1.1	(3.28).10^{-3}	(3.61).10^{-3}
DG	Disel generator	(2±0.5).10^{-2}	(1±0.5).10^{-2}	(2±0.5).10^{-4}
I	Invertor	(5±4).10^{-2}	(2±1).10^{-4}	1.10^{-5}
AB	Battery	(2±1).10^{-3}	(1±0,5).10^{-3}	2.10^{-5}
X, Y, Z	Switches	(1±0.5).10^{-3}	(2±1).10^{-4}	2.10^{-7}

TABLE II. CONDITIONAL PROBABILITY OF FAILURE OF SWITCHES

Designation	**Component**	**Failure**	**Switch conditional probability of failure Q FAILURE K**
X, Y, Z	Switches	Interruption due to short circuit At switch on	(5±2).10^{-4} (1±0.5).10^{-2}

According to the methodology presented in [19], a number of calculations of various reliability indicators were carried out, which are as follows:

- Long-term failure rate of a wind-diesel generator hybrid power plant:

$$\Lambda_{\text{long-term outage}} = 3.1.10^{-7} year^{-1} \ ;$$

- Short-term failure rate of a wind-diesel generator hybrid power plant

$$\Lambda_{\text{short-term outage}} = 3.59.10^{-3} year^{-1} \ ;$$

- failure rate of a wind-diesel generator hybrid power plant due to deteriorating wind conditions:

$$\Lambda_V = 3.14.10^{-5}\ year^{-1} \ ;$$

- relative duration of long-term failure of wind-diesel generator power system:

$$q_{\text{long-term outage}} = 1.49.10^{-9};$$

- relative duration of short-term failure of wind-diesel generator power system:

$$q_{\text{short-term outage}} = 2.51.10^{-6};$$

- Wind turbine failure duration due to deteriorating wind conditions:

$$q_V = 5.7.10^{-9}.$$

The total failure rate of wind-diesel generator power system is calculated by next expression:

$$\Lambda(\text{W}-\text{DG}) = \Lambda_{\text{long-term outage}} + \Lambda_{\text{short-term outage}} + \Lambda_V = 3.622.10^{-3}.$$

The total relative duration of failures of wind-diesel generator power system is:

$$q(\text{W}-\text{DG}) = q_{\text{long-term outage}} + q_{\text{short-term outage}} + q_V = 2.517.10^{-6}.$$

III. CONCLUSIONS

The proposed logic-probabilistic method based on a failure tree for the reliability study of a two-generation hybrid system allows for the consideration of wind-diesel generator system operation characteristics as well as meteorological conditions.

The suggested approach for a wind-diesel generator hybrid power system has the advantage of taking into consideration complex events such as: failure of one of the elements during emergency repair of the other element; and refusal to activate the switching devices.

The failure rate (Λ) and relative failure duration (q) indicators are used to assess the reliability of the hybrid wind-diesel generator power system (q). These indicators can be used successfully to select the best structure for a wind generator-diesel generator system.

The calculated values for the reliability indicators reveal that the modeled system, which consists of two wind generators with a rated power of 225 kW and a diesel unit, has reached its sustainability limit. Despite the good wind speed conditions, the proposed and investigated hybrid power system is not suited for the location of Sliven, Bulgaria. To improve system reliability, a hybrid power system should be searched for in the future. It would be better to look into a power supply system with a solar panel together with wind generator with sufficient power, as a source of renewable energy in the future.

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