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Reliability Analysis of Distributed Grid-connected Photovoltaic System Monitoring Network

FU Zhixin[a], LI Qiaomu, YUAN Yue

College of Energy and Electrical Engineering, Hohai University, 211100 Nanjing, China

Abstract. A large amount of distributed grid-connected Photovoltaic systems have brought new challenges to the dispatching of power network. Real-time monitoring the PV system can efficiently help improve the ability of power network to accept and control the distributed PV systems, and thus mitigate the impulse on the power network imposed by the uncertainty of its power output. To study the reliability of distributed PV monitoring network, it is of great significance to look for a method to build a highly reliable monitoring system, analyze the weak links and key nodes of its monitoring performance in improving the performance of the monitoring network. Firstly a reliability model of PV system was constructed based on WSN technology. Then, in view of the dynamic characteristics of the network's reliability, fault tree analysis was used to judge any possible reasons that cause the failure of the network and logical relationship between them. Finally, the reliability of the monitoring network was analyzed to figure out the weak links and key nodes. This paper provides guidance to build a stable and reliable monitoring network of a distributed PV system.

1 Introduction

In recent years, Photovoltaic (PV) power generation in the form of distributed power dominates the PV market, and has the trend of large-scale development. Affected by the uncertainty of light intensity and environment temperature changes. Adjustable control of distributed PV power is poor, at the same time, with the growing number of access points, the interconnection of distributed PV power plants to the grid has brought new challenges to the grid scheduling, the corresponding monitoring problems have also been paid more and more attention[1,2].

Aiming at the shortcomings of traditional monitoring network, many scholars at home and abroad apply sensor technology to the monitoring filed. Because of its good timeliness and flexibility, Wireless Sensor Network (WSN) technology provides new ideas to the construction of PV monitoring network[3,4]. While the studies on reliability analysis of these monitoring networks are still rare. The existing studies have mainly focused on its software, hardware and communication network's topology design[5,6], which have taken the operating characteristics of the monitoring network's constituent elements in less consideration. However, the reliability of the monitoring network based on the WSN technology is closely related to the operating characteristics of its sensor nodes: On the one hand, the monitoring network based on WSN technology is constructed by energy limited sensor nodes. So the energy issue has become one of most important factors restricting the reliability of

[a] Corresponding author : zhixinfu@hhu.edu.cn

monitoring network. On the other hand, because WSN uses wireless communication method, its channel bandwidth is narrow. Moreover, it's susceptible to the external interference from the environment and the other electromagnetic signals, which resulting in information latency, packet loss and other issues. So the communication quality has become another important factor restricting the reliability of the monitoring network[7,8]. Based on the above two points, in view of the insufficient research on the reliability of distributed PV monitoring network. This paper took fully consideration of the topological structure and the operating characteristics of its constituent elements, when analyzing the reliability of the monitoring network. It explored methods to improve the reliability of distributed PV monitoring network in order to improve its operating performance.

Given the characteristic that the reliability of the monitoring network changes with time. Firstly, this paper established a reliability model of a distributed PV monitoring network. Secondly, the fault tree analysis method was applied to determine possible causes leading to the failure of the monitoring network, and logical relationships between them. Finally, according to the simulation data, it looked for weak links and key nodes of the monitoring network, while analyzing its reliability.

2 Topological structure of PV monitoring network and its reliability evaluation indicators

2.1 Construction of the monitoring network based on WSN technology

In order to adapt to the characteristics that the number of access points of the future distributed PV systems is huge, and its access points are dispersed, the construction of the monitoring network should be simple and easy to maintain. The clustering topology of WSN has good scalability, and it is easy to manage and maintain[9], which make it suitable for the wide and scattered distributed PV systems. In this paper, based on WSN the classical triangle mesh method is used to deploy light intensity sensor nodes which are located on solar panels. This method can ensure the coverage degree of solar panels, at the same time, effectively reduce the cost and the number of sensor nodes.

Taking a $75\times60m^2$ solar panels for example. The monitoring network uses the light intensity sensor node with the perception radius of 10m. Given that the tree topology of WSN has advantages of simple structure, little energy consumption for information transmission and high efficiency. In this paper, light intensity sensor nodes use tree topology to transmit information between them. According to the energy consumption model of the sensor node, and the principle of minimum energy consumption, the cluster head node should be located at the geometric center of the solar panels, and the transmission of information uses the principle of the minimum number of hops to maximize the life of the monitoring network[10]. The deployment of light intensity sensor nodes on solar panels is shown in figure 1. In this figure, the Arabic number represents the number of each light intensity sensor node (Such as: 3 represents the No.3 light intensity sensor node). L represents the transmission path(Such as: L8 represents the No.8 transmission path).

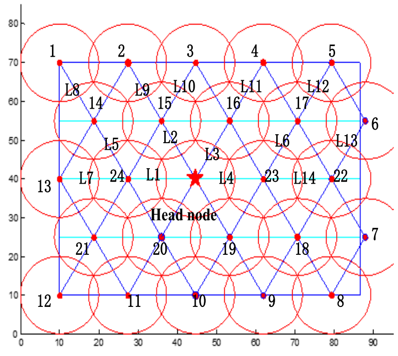


Figure 1. PV monitoring system based on triangle deployment

Figure 1 shows that, the light intensity sensor nodes are uniformly distributed on the solar panel. What's more, all sensor nodes and communication links are in a symmetrical state. Therefore, this paper considers only the light intensity sensor nodes and communication links situated on the upper part of the solar panel. The transmission paths between sensor nodes are:

$1 \rightarrow 14 \rightarrow 24 \rightarrow$ head node	$14 \rightarrow 24 \rightarrow$ head node	$2 \rightarrow 15 \rightarrow$ head node
$15 \rightarrow$ head node	$3 \rightarrow 15 \rightarrow$ head node	$16 \rightarrow$ head node
$4 \rightarrow 16 \rightarrow$ head node	$17 \rightarrow 23 \rightarrow$ head node	$5 \rightarrow 17 \rightarrow 23 \rightarrow$ head node
$22 \rightarrow 23 \rightarrow$ head node	$6 \rightarrow 22 \rightarrow 23 \rightarrow$ head node	$23 \rightarrow$ head node
$13 \rightarrow 24 \rightarrow$ head node	$24 \rightarrow$ head node	

2.2 Reliability evaluation indicators of the monitoring network

The coverage degree and the connectivity degree are two basic evaluation indicators to evaluate the reliability of the distributed PV monitoring network. The coverage degree reflects the collection reliability of light intensity information and other physical information of the monitored area. And the connectivity degree reflects the information transmission reliability between sensor nodes. Therefore, the coverage degree and the connectivity degree affect directly the monitoring quality of the monitoring network. So they are important evaluation indicators to evaluate the reliability of the monitoring network. According to the reliability evaluation indicators proposed in research [11], this paper makes the following definitions for the factors which affect the reliability of the distributed PV monitoring network: (1)Failure rate of light intensity sensor nodes. It is the ratio of the number of failure nodes to the total number of sensor nodes. It reflects the impact of the failure nodes to the performance of the monitoring network. (2)Coverage degree. It is the ratio of the effective coverage area to the total monitored area. It reflects the effective coverage ratio in the case of the failure of sensor nodes. (3)Reliability of the communication links. It is used to judge if the light intensity information or other information can be transmitted correctly between sensor nodes. It reflects the reliability of the transmission of information when the nodes are in normal working condition. If any one of these three indicators can't achieve the monitoring network's reliability evaluation indicators, it means that the monitoring network fails.

According to the monitoring network's requirement to the reliability of data, set the reliability evaluation indicators as follows: When the failure rate of light intensity sensor nodes reaches 20%, the coverage degree of the solar panel decreases to 80%, or 20% or more light intensity information can't be transmitted correctly to the cluster head node, it means that the monitoring network fails.

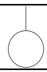
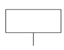
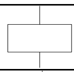
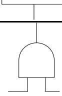
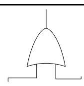
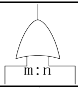
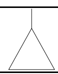
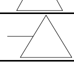
3 Fault tree model of PV monitoring network

3.1 Advantages of fault tree analysis method

The Fault Tree Analysis (FTA) method has the characteristics of strong logical, analytical simple, computationally efficient, etc[12], which make it have obvious advantages in assessing risks and tracking weak links of systems with complex structure. Thus, it has been widely used in the actual projects. This paper set the failure of the monitoring network as the Top Event in the FTA method. Then according to the topology of the monitoring network and the information transmission paths between sensor nodes, it analyzed any possible causes leading to the failure of the monitoring network layer by layer. After that, it established the fault tree model of the monitoring network with the help of specific event symbols, logical gates and transfer symbols. Table 1 shows the basic logical symbols and the corresponding relationships with the monitoring network's elements when analyzing the reliability of the distributed PV monitoring network using the FTA method.

Depending on the operating characteristics of the distributed PV monitoring network, the steps to analyze the reliability of the monitoring network with FTA method are as follows: (1)Determine the top event of the fault tree, which means the failure of the monitoring network. (2)Making logical analysis to determine the possible causes of the failure of the monitoring network. (3)Establish the fault tree model of the failure of the monitoring networt. (4)Making qualitative and quantitative analysis of the fault tree model.

Table 1. Symbols of monitoring system's fault tree model

Symbol	Symbol	Name	Explanation	Correspondence with monitoring network
Event Symbol		Basic Event	Event which can not or don't Need to break down	Failure of sensor nodes or communication links
		Top Event	Target Event of Fault Tree	Failure of monitoring network
		Intermediate Event	Located between Top Event and Basic Event	Possible causes of the failure of the monitoring network
Logic Gates		AND gate	Output event occurs only when all input events occur	
		Or gate	Output event occurs as long as one input event occurs	
		Vote gate	Output event occurs when the *m* of *n* input events occur	
Transfer Symbol		Transfer-in		
		Transfer-out		

3.2 Qualitative analysis of the monitoring network's fault tree model

On the basis of the previous analysis, it needs to make further qualitative analysis of the fault tree model of the monitoring network. Before making the qualitative analysis, this paper firstly made the following assumptions: (1)The Top Event and Basic Events of the monitoring network's fault tree model only have two states: normal state and abnormal state. And the failures of these events are independent. (2)"1" means abnormal state, "0" means normal state. (3)The malicious destructions of the human beings and the interferences from the external environment to the performance of the monitoring network are not taken into consideration. (4)E represents Basic Events of the fault tree model, F represents its Top Event. Then, $X_i = \phi(E_i)$, $F = \phi(X_1, X_2 \cdots X_n)$.

$$X_i = \begin{cases} 1, \text{ Basic Event occurs} \ (i = 1,2,\cdots n) \\ 0, \text{Basic Event doesn't occur} \ (i = 1,2,\cdots n) \end{cases} \tag{1}$$

$$F = \begin{cases} 1, \text{ Top Event occurs} \\ 0, \text{ Top Event doesn't occur} \end{cases} \tag{2}$$

The state of the Top Event F is determined by the states of Basic Events X, $F = \phi(X_i)$, ϕ represents the structure function of the fault tree model. If the number of Basic Events is n, then with AND-gate, the structure function F can be expressed as:

$$F = \phi(X) = \bigcap_{i=1}^{n} X_i = \prod_{i=1}^{n} X_i \tag{3}$$

With Or-gate, it can be expressed as:

$$F = \phi(X) = \bigcup_{i=1}^{n} X_i = 1 - \prod_{i=1}^{n} (1 - X_i) \tag{4}$$

If all the events in one Basic Event occur will lead to the occurrence of the Top Event, this Basic Event is called a cut set. If any one event in this Basic Event is removed, this Top Event will no longer occur, then this cut set is called the smallest cut set. The process to make qualitative analysis of the monitoring network's fault tree model is the process to find the smallest cut set. The common methods to find the smallest cut set of the fault tree model are: upward method, downward method, Boolean cut set method, ect. This paper used the downward method to find out the smallest cut set of the monitoring network's fault tree model.

3.3 Establishment of the monitoring network's fault tree model

This paper analyzed the reliability of the distributed PV monitoring network running for one year. The Top Event of its fault tree model is the failure of the monitoring network. The external interference is not taken into consideration, according to the reliability evaluation indicators proposed previously, the failure of the monitoring network is caused by three aspects: (1)The rising of the failure rate of light intensity sensor nodes. (2)The decreasing of the coverage degree of the solar panels' monitored area. (3)The decreasing of the reliability of information transmission due to the failure of the communication links. The main fault tree model of the failure of the monitoring network is shown in figure 2. Then, this paper analyzed respectively the failure of the monitoring network caused by these three aspects.

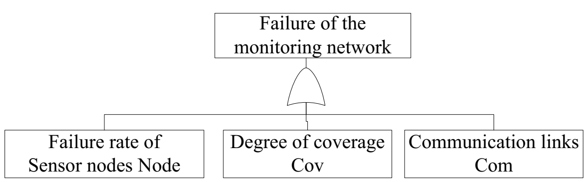


Figure 2. Main fault tree model of the failure of the monitoring network

3.4 Reliability of communication links

According to the information transmission paths established in section 1, the fault tree model of communication links is shown in figure 3.

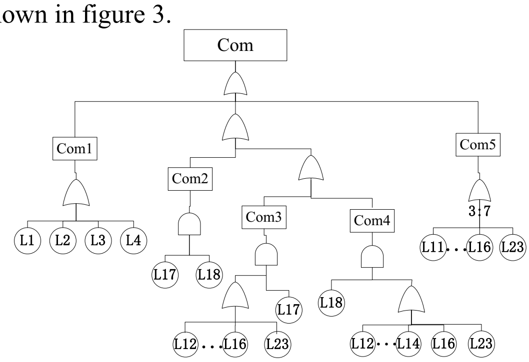


Figure 3. Fault tree model of communication link

3.5 Coverage degree

The reasons which may cause the decrease of the solar panel's coverage degree, can be divided into the following three groups: (1)The decreasing of coverage degree is caused only by boundary nodes. (2)The decreasing of coverage degree is caused only by internal nodes. (3)The decreasing of coverage degree is caused by both boundary nodes and internal nodes. The triangular grid method proposed in [13] is utilized to calculate the effective coverage area of the monitored area. The fault tree model of the solar panel's coverage degree is shown in figure 4.

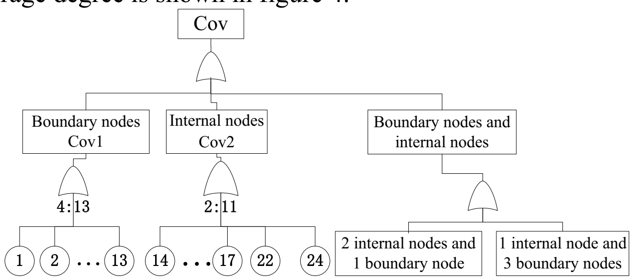


Figure 4. Fault tree model of the coverage degree

3.6 Failure rate of light intensity sensor nodes

For the sensor node *i*, who is responsible for receiving a number of *n* nodes' information, its abnormal working states can be presented as: (1)The node *i* fails itself. (2)The number of information received successfully by the node *i* is less than *n*. For example: For the node No.23, when it is under normal working state, it should receive 7 light intensity messages transmitted respectively from node No.5, 6, 7, 8, 17, 18 and 22. If one or more in these seven nodes fail, then the node No.23 can't receive 7 messages successfully, which means it is in an abnormal working state. Else, if the node No.23 fails itself, of cause, it is also under an abnormal working state. According to the information transmission paths established earlier, by analyzing the logical relationships between the monitoring network's sensor nodes, the fault tree model of the sensor nodes' failure rate is as shown in figure 5.

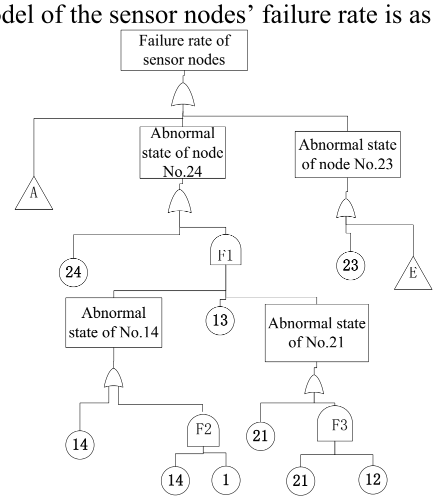


Figure 5. Fault tree model of sensor nodes' failure rate

In this fault tree model, E represents: except node No.23 fails itself, all the other causes leading to its abnormal working state. A represents: except node No.23 and No.24 themselves are in abnormal states, all the other causes causing the increasing of the sensor nodes' failure rate. For the PV monitoring network constructed in section 1, through analyzing the logical relationships between sensor nodes, the sub-fault tree E and A can be shown respectively in figure 6 and figure 7.

In the sub-fault tree A. B represents any one node inNo.14, 16, 17 or 22 is in an abnormal working state. C represents two or more nodes in No.14, 16, 17 and 22 fail. D represents three or more nodes in No.1, 2, 3, 4, 5, 6 and 13 fail. When establishing the sub-fault trees B, C, and D, it should use the Or-gate and Vote-gate. This paper no longer gives specific presentations of them.

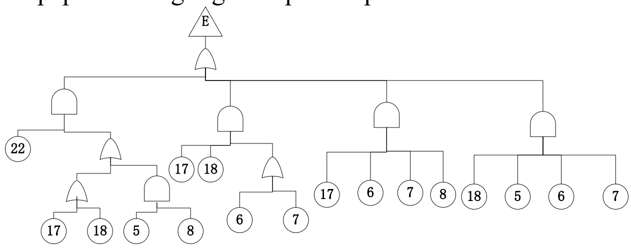


Figure 6. Sub-fault tree E

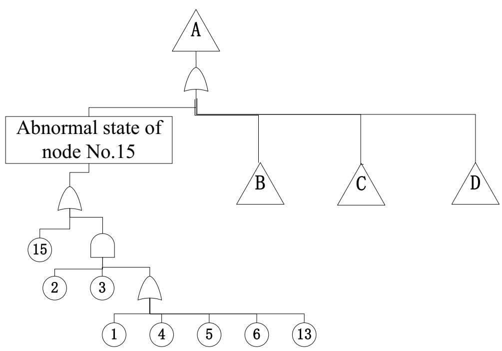


Figure 7. Sub-fault tree A

3.7 Finding the smallest cut sets with the downward method

The basic theory of the downward method is: From the Top Event of the fault tree model, according to the established logical relationships, analyze layer by layer from the top to the bottom until that the Top Event can be expressed by Basic Events. Then find the smallest cut sets of fault tree models with Boolean algebra rules.

Took the node No.24 as an example, searches for the smallest cut set which may cause the abnormal working state of the monitoring network. The solving process is as shown in table 2. In this table, *G* represents abnormal working state of sensor nodes, *E* represents Basic Event, *F* represents the collection of Basic Events. For example, G_{24} represents the abnormal working state of the node No.24. E_{24} represents the node No.24 fails itself. F_2 represents nodes No.1 and No.14 fail at the same time. It is the collection of E_1 and E_{14}, written as E_1E_{14}.

Table 2. Solving Process of the smallest cut-set by the downward method

G_{24}	E_{24}	E_{24}	E_{24}	E_{24}	E_{24}
	F_1	$E_{13}G_{14}G_{21}$	$E_{13}E_{14}G_{21}$	$E_{13}E_{14}E_{21}$	$E_{13}E_{14}E_{21}$
			$E_{13}F_2G_{21}$	$E_{13}E_{14}F_3$	$E_{13}E_{14}E_{12}E_{21}$
			$E_{13}G_{14}E_{21}$	$E_{13}F_2E_{21}$	$E_{13}E_1E_{14}E_{21}$
			$E_{13}G_{14}F_3$	$E_{13}E_2E_3$	$E_{13}E_1E_{14}E_{12}E_{21}$
				$E_{13}E_{14}E_{21}$	$E_{13}E_{14}E_{21}$
				$E_{13}E_2E_{21}$	$E_{13}E_1E_{14}E_{21}$
				$E_{13}E_{14}F_3$	$E_{13}E_{14}E_{12}E_{21}$
				$E_{13}F_2F_3$	$E_{13}E_1E_{14}E_{12}E_{21}$

The last column of this table shows all cut sets that may cause the abnormal working state of the node No.24. After simplifying with Boolean algebra rules, the smallest cut sets X_1 and X_2 can be obtained respectively.

$$\begin{cases} X_1 = E_{24} \\ X_2 = E_{13}E_{14}E_{21} \end{cases} \tag{5}$$

$$G_{24} = X_1 + X_2 \tag{6}$$

In the same way, the smallest cut set which may lead to the abnormal working state of the node No.23 can be written as:

$$\begin{aligned} G23 = {} & E_{23} + E_{17}E_{22} + E_{18}E_{22} + E_5E_8E_{22} + \\ & E_6E_{17}E_{18} + E_7E_{17}E_{18} + E_6E_7E_8E_{17} + E_5E_6E_7E_{18} \end{aligned} \tag{7}$$

It can use the same method to solve the smallest cut sets of the other fault tree models. This paper no longer show them one by one.

4 Simulation analysis

In the simulation, the expectancy of life of the light intensity sensor nodes is $10^6 h$, then $\lambda=10^{-6}$. The bit error rate is $p_{\mathrm{bit}}=0.2\times10^{-3}$. The length of data frame of light intensity information is $l_{\mathrm{n}}=65\times8bit$. The simulation time is $T_{\max}=24\times365h$.

The times that Basic Events occur caused by the failures of communication links and sensor nodes, are shown respectively in figure 8 and figure 9. Comprehensively consider the figure 1, figure 3 and figure 8, it can be known that the communication links connected directly with the cluster head node have the most important influence on the operation of the monitoring network. It could take the retransmission mechanism or increase the number of communication paths between sensor nodes to improve the reliability of the information transmission. From figure 1 and figure 9, it can be known that the failures of node No.23 and node No.24, which are connected directly to the cluster head node, are the main causes causing the failure of the monitoring network. Thus, in the operation of the monitoring network, it should focus on the working states of node No.23 and No.24. Once their working states are abnormal, they should be repaired immediately.

According to the simulation results showed in figure 8 and figure 9, in 10^5 times of simulation, different causes causing the failure of the monitoring network are shown in table 3. In this table, Node represents the failure rate of sensor nodes, Cov represents the coverage degree, Com represents the reliability of communication links. According to table 3, the decreasing of the reliability of communication links is the main cause which may lead to the failure of the monitoring network. Therefore, to improve the reliability of the monitoring network, it should make efforts to improve the reliability of the communication links, and to ensure the precise information transmission.

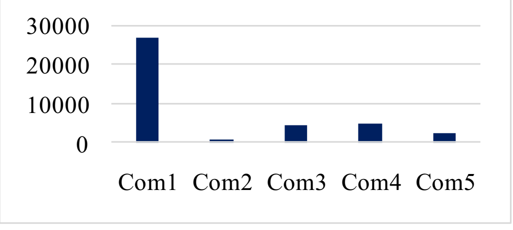


Figure 8. Times that basic events occur caused by the failure of communication links

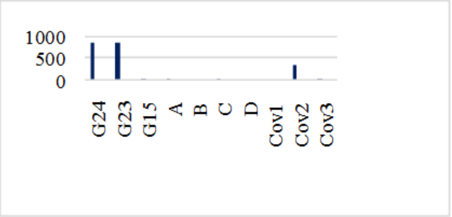


Figure 9. Times that basic events occur caused by the failure of sensor nodes

Table 3. Occurrence of different failure causes

Node	Cov	Com
1871	416	39621

5 Conclusion

This paper built a reliability model of a distributed PV monitoring network based on WSN technology. On the basis of fully considered the dynamic changes of its failure, the FTA method was used to determine any possible causes which may cause the failure of the network. The results of this paper offer the thought for further research on the reliability of the distributed PV monitoring network.

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