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Bayesian Networks Application to Reliability Evaluation of Distribution Systems Containing Micro-Grids or Looped Network

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Abstract

It is one of the effective methods to improve the reliability of the distribution system by using looped network power supply. With the development of new energy technology, distributed generation has been more widely used. But a small power system named micro-grid which is assembled by the device such as distributed generation, energy storage device and controllable load in a certain operating rules catches the attention of people. It can operate in islanded mode with the power grid failure, which can greatly improve the reliability of the system. Traditional analytical method and Monte Carlo method are difficult to evaluate its reliability accurately. In this paper, a new artificial intelligence method based on Bayesian networks is used for the system reliability analysis and evaluation. The corresponding Bayesian networks are established for the reliability test bus 2 which containing looped network and the improve reliability test bus 6 which containing micro-grids separately. With the help of causal reasoning and diagnostic reasoning, the supply influence of different types of DG output intermittent, operation mode on loads are detected, the key factors which have an impact on important load power supply reliability are found out, which is the theoretical foundation for practical engineering decision, so as to improve system reliability, identify failures and make maintenance scheduling.

Keywords*: micro-grid; looped network; distribution system; reliability evaluation; Bayesian network*

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1. Introduction

In recent years, driven by the problems of environment and energy, many countries in the world attached great importance to the development of renewable energy power generation , such as wind power, photovoltaic batteries, fuel cells and the micro gas turbine distributed power, but a small power system named micro-grid which is assembled by the device such as distributed generation(DG), energy storage device, controllable load in a certain operating rules catches the attention of people ,and it is considered to be the future development direction of power system. Micro-grid is a small power distribution system; it can operate in grid-connected or grid-off mode. The micro-grid general access to the power distribution system, it can operate in grid-connected or grid-off mode when the power grid failure or need to disconnect to the main system, namely the island [1-2].

With the micro-grid access distribution system, the traditional single power supply radial distribution system will be turned into a new power distribution system with more power supply and load, which will change the structure of the radial distribution system, and the power flow of distribution network will be two-way. It will bring some new

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problem to the reliability evaluation of distribution system when we take some factors into consideration, such as island running and the uncertainty of the output power, which will have great changes for the reliability assessment theory and method of power distribution system.

Micro-grid has produced important influences on the power supply reliability of distribution system, but also greatly increased the complexity of the distribution system when analysis reliability. Scholars at home and abroad make related research. In the terms of the reliability model for distributed generation, Reference [3] discusses the time sequential calculation method for distribution system reliability when wind power as a backup power access system; Reference [4] build a mathematical model of photovoltaic power generation and wind power, presented network reliability evaluation algorithm based on the simulation method, but not considering the influence of energy storage on the network reliability; All of above reference will provide the beneficial reference for reliability evaluation for the new distribution system containing micro-grid in terms of the modeling of a distributed power supply and load and the calculation of the reliability index.

At present, there are only two approaches, analytical approach and Monte-Carlo Simulation approach, used to calculate the reliability indices, quantitative evaluation for the system reliability level. It is difficult to effectively identify the muzzle bottleneck link in power system reliability, in order to guide the planning and operation department to take effective measures to improve the reliability of the system. In view of the limitations of traditional reliability algorithm, Reference [5] is the first paper to apply BN in reliability evaluation of interconnected power systems, analyzes the probability of each generator capacity and the failure rate of power index; Reference [6] make some study on applying BN to reliability evaluation of power stations or distribution systems for the first time, calculate the related system reliability index, find out the weak links of system reliability with the Bayesian network through causal reasoning and diagnostic reasoning; Reference [7] make distribution system reliability evaluation on the substation power, compared to the probability importance structure importance degree and key importance; Reference [8] used the Bayesian network interval algorithm in distribution system reliability evaluation, further consider the possible range of component reliability parameters. Reference [9-10] do not consider the impact of DG units upon the power systems Reference [11] consider the DG and Micro grids, but it used Monte Carlo Simulation method to evaluate distribution system reliability.

In this paper, various types of multi-state reliability models of micro-grid are build, the corresponding Bayesian networks are established for the reliability test bus 2 which containing looped network and the improve reliability test bus 6 which containing micro-grids separately, the form principle of the island are expound with the distribution system failure. With the help of causal reasoning and diagnostic reasoning, we could detect the supply influence of different types of DG output intermittent, operation mode on loads, and find out the key factors which have an impact on important load power supply reliability, then identify the weak links of the whole system.

2. The Establishment of the Bayesian Network for Distributed Generation

2.1. The Overview of Bayesian Network

Bayesian Network is a directed graphic description of probability relations; it provides a method which can turn knowledge intuitively to graphic visualization. A Bayesian network is a directed acyclic graph (DAG); each node only corresponds to a random variable, the conditional probability value of node corresponding to the value of a random variable. The directed arcs represent the condition between the nodes in the graph (causal) dependencies. Each joint probability distribution of the basic system can get by the conditional probability distributions and network topology. It suggests that using the Bayesian network model can calculate the probability index so as to assess the reliability of power system.

2.2. Bayesian Network of Distribution System

Each component in the distribution power system corresponds to a node in the Bayesian network, so the Bayesian network is composed of a number of nodes, the building process of a Bayesian network is, in fact, through continuous traversal, to determine the logical relationship between nodes. There are four logical relationships for the Bayesian network node in the power distribution system, they are "or”, “and", "union" and "cause-and-effect" relationship respectively [9], which is shown in Figure 1. Capital letters (A, B, C)represent node variables and their corresponding lowercase letters (a, b, c) represent node variable specific values, 1 indicates normal (the element exist) , 0 indicates failure (or this element does not exist). For example, the semantic interpretation of the "causal" node model is in the first line of the probability table, it can be expressed as p (c = 1 | a = 0, b = 0) = 0.025, its semantic interpretation is the fault probability of c is 0.025 where a and b are in fault (a and b represent the element does not exist).

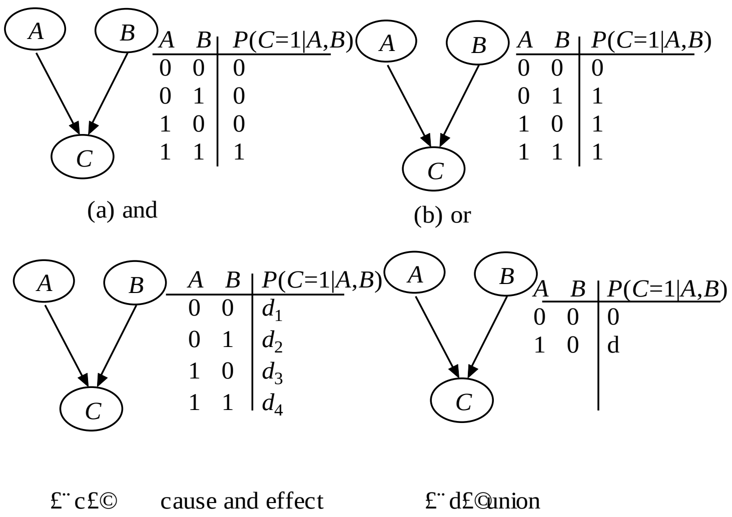

Figure 1. Models of Node Relations in Bayesian Network

The calculation process of the traditional distribution system reliability index is according to average annual failure rate of each component, and the annual mean time to repair to calculate load-point failure rate λ_s, average outage duration r_s and average annual outage time U_s for load point s, Then calculate the reliability index in the system, such as System Average Interruption Frequency Index SAIFI, the Customer Average Interruption Frequency Index CAIF, System Average Interruption Duration Index SAIDI, Customer Average Interruption Duration Index CAIDI, Average Service Availability Index ASAI and Average Service Unavailability Index ASUI, *etc.*

The above-mentioned method is simple, the model is accurate, but for larger systems, with the increasing numbers of components and operating modes, the evaluation of system will become very difficult. Generally, it cannot give the position of quantitative components in the whole system reliability. Based on the traditional calculation method of theory, we can calculate the reliability index of each load point and system according to the reliability index of each component directly based on the Bayesian network model, analyses quantitatively the effects of components on the system reliability index. From the perspective of improve system reliability, the Bayesian network model is divided into the following two cases:

A. The operation mode of the distribution system is a looped network with the contact switches, such as RBTS bus2, which is shown in Figure 2. Feeder 3 and feeder 4 constitute one ring network through contact switch A; Feeder 1 and feeder 2 constitute another ring network through contact switch A. The load point could get electricity from the other direction through the contact switch function to ensure the partial load power supply when a line failure occurs, so this power supply mode could improve the reliability of distribution system. For this kind of complex distribution network, we can draw the corresponding Bayesian network according to the physical topology and the causal relationship between components. This Bayesian network model has more nodes and the complex structure.

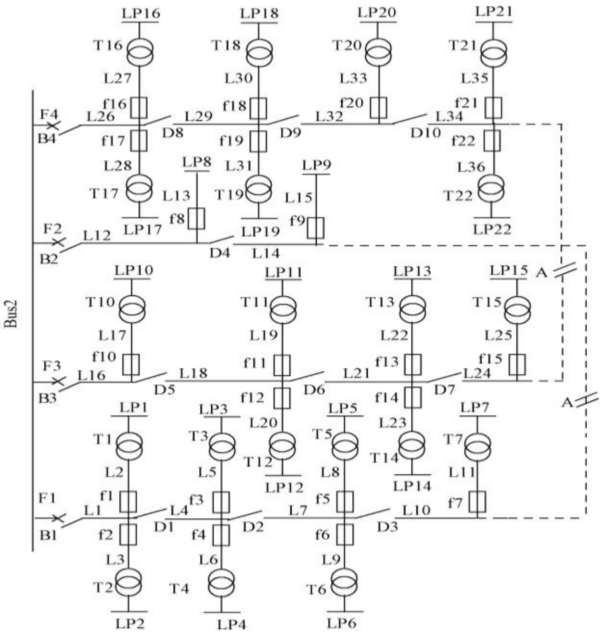

Figure 2. Distribution System for RBTS Bus2

B. The operation mode of the distribution system is a radial network with no contact switches, which is shown in Figure 4. The load point could not get electricity from the other direction when a line failure occurs, but the reliability of the system could be improved when micro-grid run in island mode. It can be equivalent for this kind of distribution system, and then we can build the corresponding Bayesian networks. The Bayesian network model has fewer nodes and the simple structure, such as improved RBTS bus 6 [13], it is shown in Figure7.

2.3. The Reliability Test System

In this paper, we take RBTS bus 2 as experiment system; apply the proposed method to analysis the reliability. This system has a 33KV substation, 4 outlines, 22 load points, 1908 subscribers, the total average load is 12.291 MW, and maximum peak load is 20 MW. The system wiring is shown in Figure 2. The reliability parameters of components all quote from literature [12-13]. This paper adopt the fifth connection mode, there has isolating switch in main feeder, has branch protection and standby power, the Bayesian network of feeder 3 is shown in Figure 3.

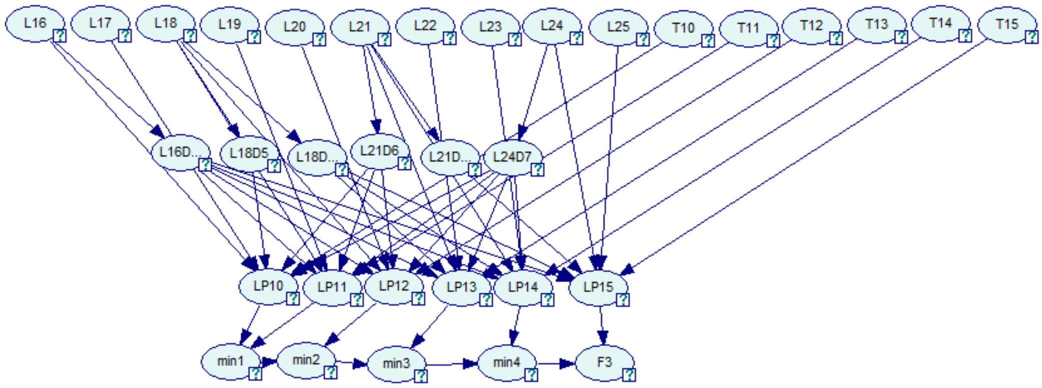

Figure 3. Bayesian Network of Feeder 3

The reliability of distribution system based on Bayesian networks of feeder F3 can be obtained, which is equal to the data from reference [12], it indicates that the Bayesian networks method can be used to reliability assessment of power distribution system, we can obtain reliability index for all feeder of bus 2, and it is shown in Table 1.

Table 1. The Reliability Index of Bus 2

Index / Feeder	ASAI	ASUI	SAIDI	ENS	AENS
F1	0.999912	8.77131E-05	0.768366756	2.78381556	0.004270
F2	0.999940	5.97312E-05	0.523245312	1.12205154	0.561026
F3	0.999912	8.83265E-05	0.773740140	2.35103945	0.003720
F4	0.999914	8.61976E-05	0.755090976	2.58680889	0.004159
S	0.999913	8.73000E-05	0.764614848	8.84371544	0.004635

Based on Bayesian network diagnosis inference, each component's posterior probability can be computed on the condition of system failure, Figure 4, is the result of each component's failure probability on the condition of system failure. According to figure 5, we can know that in the failure probability of feeder line, L18 is larger, while L22 and L23 are smaller. But for the transformers, T10、T11、T12 is larger, T13、T14 is smaller. So L18, T10-T12 principally affect the entire system reliability in turn, these elements' availabilities should be increased to enhance the entire system reliability.

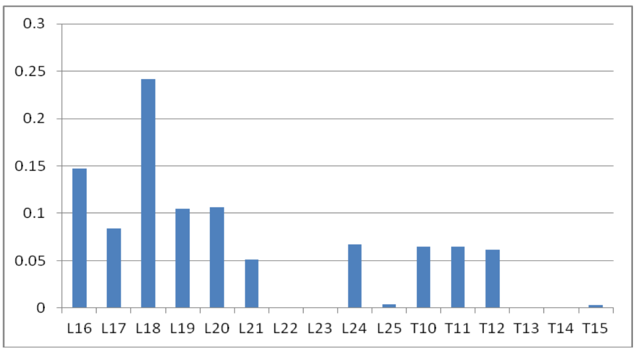

Figure 4. Fault Probability of Elements for Bus2 Feeder 3

3. The Reliability Evaluation of the Distribution System Containing Micro-Grid

3.1. The Reliability Model of the Distributed Generation

Due to the nature of distributed generation output power is different, the different reliability models should adapt to the different types of DG. In this paper, the reliability model can be divided into two classes [14-15].

(1)DG is equivalent to a rated capacity of power supply

DG is equivalent to a rated capacity of the generator; it can only meet the load requirements in the island which is no more than the rated capacity. According to the rated capacity of DG, based on the technical conditions of power balance on the power, we can divides the distribution generations as island, in order to guarantee the island operate placidly. This power supply model only has influence on the reliability index of the load point within the island. It has no effect on the reliability index of outside of the island, such as wood oil generating units, hydropower, and gas turbine power generation. This type of DG can be represented in two state models. ① the fault state: the output power is zero;②the normal state: the output power of the generator is close to the rated power, the state models are shown in Figure 5.

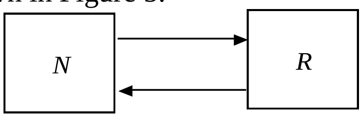

Figure 5. The Equivalent Model of the Rated Capacity of Generator

In the model, N represents normal operation state, R represent repairing state. Assuming that the failure rate λ_R, repair rate μ_R for DG, the probability of the normal operation of the P_N, repair state probability P_R are as follows:

$$P_N = \frac{\mu_R}{\mu_R + \lambda_R} \tag{1}$$

The availability is

$$A = P_N \tag{2}$$

The unavailability is

$$U = 1 - A = P_R \tag{3}$$

(2) DG is equivalent to random power supply

The output power of this model are largely depends on the characteristics of renewable resources and the parameters of generator. Such as wind power generation and photovoltaic power generation systems. Due to the energy resources are greatly influenced by the weather and climate, the randomness of output power is very large. So the reliability model of this kind of distributed power supply is equivalent to a generator model with several capacity states, the state model is shown in Figure 6.

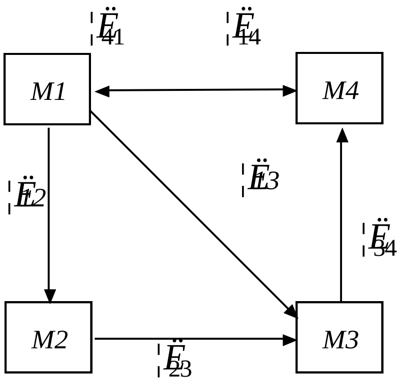

Figure 6. The Equivalent Model of the Random Capacity of Generator

In this case, DG can only satisfy that part of the load in the island whose output is behind the level of the DG's output power, we should consider the probability of the island's continuous power supply problems.

3.2. Island Partition Algorithm of Micro-Grid

Due to the limited capacity of DG, the output is also fluctuant, after a power failure occurs, we should compare the output power of the DG and the total load in the island. we need consider the probability distribution of the efforts of DG when we design the DG, carving out the biggest range of DG's power supply (the largest island's scope) , and install a number of section switches, in order to cut off part of the load timely when the output of DG is insufficient

After a fault happens in distribution system, DG will first exit the operation, the relay protection act, and isolate the corresponding fault components, then connected to the DG (if possible).[16] If the area is isolated from the main power grid and has no contact switch, then it can be powered by DG to form the islands operation. This paper consider island operation plan, according to the important degree of different customers, to give each customer a certain weight. When the island operation condition is satisfied, according to the priority of the important costume, it gradually increases the load until the total load and the DG output become balance. That is to say, compare the size of DG output and the load, when DG output is greater than the load, we add the other load and compared with it, and until the DG output cannot satisfy the needs of total load in an island. Its mathematical model is:

$$P_{DG} \geq \sum_{i \in D} P_{LP(i)} \tag{4}$$

P_{DG} is the output power of DG, $P_{LP(i)}$ is the capacity of load point i , D is the largest range island.

3.3. The Reliability the Improved Reliability Test System

The example system is come from the improved reliability test system. We add two DG to the joint of branch line 20 and 21, and the joint of branch line 26 and 27. When a failure occurs in the upstream supply, through the circuit breaker operation, micro-grid 1 and micro-grid 2 is formed to islands, continue to the island's load power supply, the largest range islands are respectively LP14-LP18and LP19-23, which is shown in Figure 7.

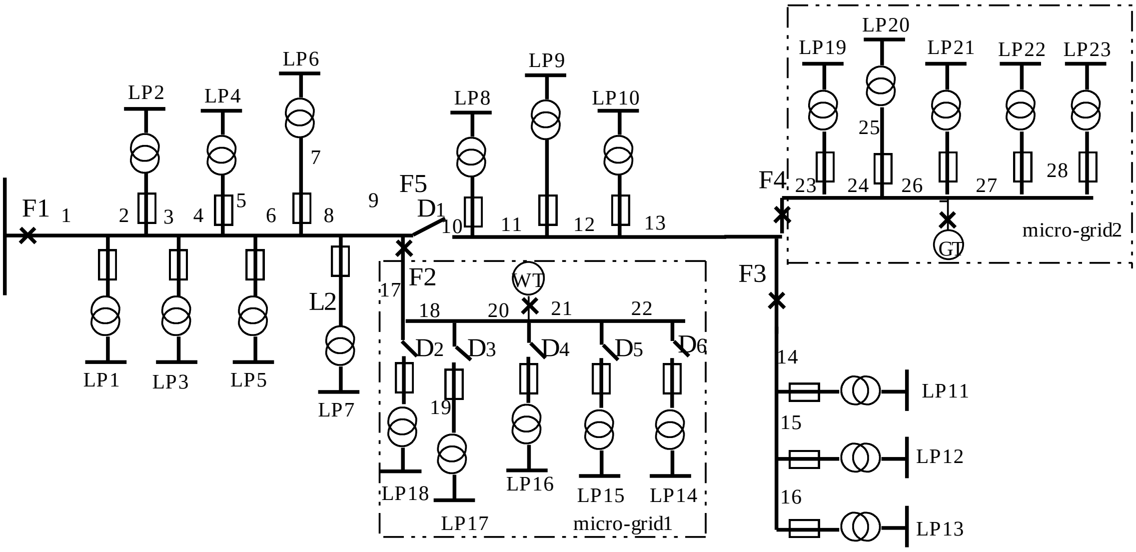

Figure 7. The Improved Test System for RBTS Bus6

To avoid unplanned island operation, this paper evaluate the influence of DG on distribution network reliability assumed DG exit distribution system when the component failure firstly, and then DG re-engage the system according to the situation, forming plan island operation, after the failure to eliminate, the plan island restore to the power the large power grid with the method of splitting.

For ease of comparison and analysis, consider the following modes:

Mode1: No DG

Mode2: At the branch line 20-21 join wind turbine, the maximum output power is 1.2 MW, the largest island is formed in the range of LP14- LP18. The important loads of island are LP14, LP15, LP17, LP16, and LP18 in turn, and add the corresponding operation element D2−D6, if the output power is lower than 0.3MW, the island could not form. When the instantaneous output power were 0.3MW,0.7MW and 1.2 MW, calculate the system reliability index separately, it is shown in table 2. Assuming that DG failure rate is 5 times per year, repair time is 50 hours per time.

Mode3:In the branch line 26-27 join gas turbine, due to the gas turbine output is relatively stable, the constant power output model is adopt to capacity of 1.2 MW, calculating the system reliability index.

Mode4:In branch line 20-21 and line 26-27 join the wind turbine and gas turbine separately, the capacity are both 1.2 MW, calculating system reliability index.

Table 2.The Point Load and System Reliability Index in Different Kinds of Mode

mode \ LP(S)	LP1-7	LP8-10	LP11-13	LP14-18	LP19-23	S
1	0.999103	0.998779	0.998528	0.998714	0.998397	0.998838
2 (0.3MW)	0.999103	0.998779	0.998528	0.998723	0.998397	0.998839
2（0.7MW)	0.999103	0.998779	0.998528	0.998730	0.998397	0.998840
2（1.2MW)	0.999103	0.998779	0.998528	0.999245	0.998397	0.998909
3	0.999103	0.998779	0.998528	0.998714	0.999337	0.998964
4	0.999103	0.998779	0.998528	0.999245	0.999337	0.999035

From Table 2, we can obtain the conclusion:
(1) From the above operating modes, we can see that the Average Service Availability Index is increased after joining the distributed generation, the Average Service Unavailability Index are decreased. The load Service Availability Index is increased with the joining of DG only to the island in the scope. That is to say, the micro-grid can run in island mode during the power failure, in order to ensure the power supply of the network load, but distributed generation had no effect on the load not in the island.
(2)Due to output power of the wind turbine are fluctuations randomly, according to the priority, when the output power is 0.3 MW, the output power is only supply to LP14; when the output power is 0.7 MW, the power is supply to LP14 and LP15; when the output power is 1.2 MW, the scope of power supply are LP14- LP18. LP14 is preference to the power supply.
(3)Compared to the mode 3 and mode 4, under the same capacity, we can see the island is closer to the end of the distribution system, the higher the reliability of the system. The more number of distributed generations, the higher supply reliability
(4) In micro-grid1, calculate the impact on reliability consider distributed generation failure rate λ_s and the outage time r_s, it is shown in Table 3. We can see the failure rate and repair time of distributed power has more impact on Average Service Availability Index. The long time of failure rate and repair time, the smaller of Average Service Availability Index, so we can improve the reliability of the system through reduce the failure rate and repair time of the element.

Table 3. The Reliability Index Considers λ_s and r_s of Distributed Generation

λ_s	r_s	ASAI	ASUI
5	50	0.998909	0.001091
30	50	0.998907	0.001093
5	10	0.998910	0.001090

4. Conclusion

This paper proposed a novel approach to the distribution system reliability analysis and evaluation. The corresponding Bayesian networks are established for the reliability test bus 2 which containing looped network and the improve reliability test bus 6 which containing micro-grids separately. With the help of causal reasoning and diagnostic reasoning, the effect on system reliability of each component can be clearly presented. At the same time, the supply influence of different types of DG output intermittent, operation mode on loads are detected, the key factors which have an impact on important load power supply reliability are found out, which is the theoretical foundation for practical engineering decision, so as to improve system reliability, identify failures and make maintenance scheduling.

In this paper, we think about the matching problem of the distributed generation and load power only, but did not consider the island formation probability and its stability, and it can reduce system reliability index if the island could not form .This problem will be a further research topic for the micro-grid and smart distribution systems in the future.

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