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Numerical and Analytical Approaches to Assessing the Reliability of Routing Algorithm in Energy Internet

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Abstract

The Energy Internet (EI) is a comprehensive and integrated system that encompasses various aspects of energy production, storage, transmission, conversion, and utilization. It involves a diverse set of technologies such as resources, devices, equipment, systems, communication, and information. A suitable index evaluation method that covers three dimensions: energy, economy, and network-system needs to be established to evaluate the performance and development of the EI in different regions and scenarios. Such a method can provide guidance and feedback for the optimization and sustainability of the EI. In this article, one aspect of the index evaluation method is focused on: the reliability assessment of a local EI that incorporates multiple energy systems. The power system is considered as the core component of the local EI and its interaction with other energy systems such as heat and gas are examined. The problem of power transmission failures that may occur due to various factors such as weather conditions and equipment faults. A reliability assessment method that considers multiple power suppliers with different transmission paths and load distributions is proposed which is assessed through Monte Carlo simulation and Markov model. The normal distribution function is used to model the load fluctuations in each transmission line and the power allocation among different paths is optimized. the case study is then presented to demonstrate the effectiveness and applicability of the proposed method. The results show that by using two transmission paths with equal power ratios, the power loss can be significantly reduced and the reliability of power delivery can be improved when there is a high load demand on the lines.

Keyword: Failure rate; Energy Internet; Internet of energy; Monte Carlo simulation; Reliability; Renewable Energy; Routing

Introduction

Energy is the fundamental force and basis of social and economic activities, as well as the precondition for human survival and development [1]. The Internet, on the other hand, has profoundly changed the way people live and work and has also brought continuous innovation and transformation to various traditional industries. In this context, it is imperative to achieve a deep integration of the Internet and the power grid, with power generation as the core [2]. To address this challenge, a new concept of Energy Internet (EI) has emerged, which is an advanced multi-grid flow system based on distributed energy resources that integrate the power system, the Internet and other information technologies, decentralized renewable energy sources, the transportation network, and other systems [3], [4]. The EI adopts a power network architecture that incorporates cold, heat, gas, and other forms of energy networks. It can realize a wide connection to distributed energy sources and market transactions to maximize the utilization of new, green, low-carbon energy sources [5]. Fig. 1 shows the main components of the EI implementation that enable bidirectional sharing and transfer of energy among different networks. The EI has attracted considerable attention from both academic and industrial sectors because it combines two pillars of modern society: the Internet and the energy network [6], [7]. In early 2008, the Future Renewable Electric Energy Delivery and Management (FREEDM) project was initiated to develop the EI in the United States [8]. In addition, Germany launched its own EI Program and E-Energy Concept under its Federal Ministry of Economics and Energy [9]. The smart grid serves as a key component for electricity transmission in EI as electricity is one of its primary forms of energy [10]. The normal operation of EI largely depends on data collection in its system which must satisfy three requirements: transmission delay minimization;

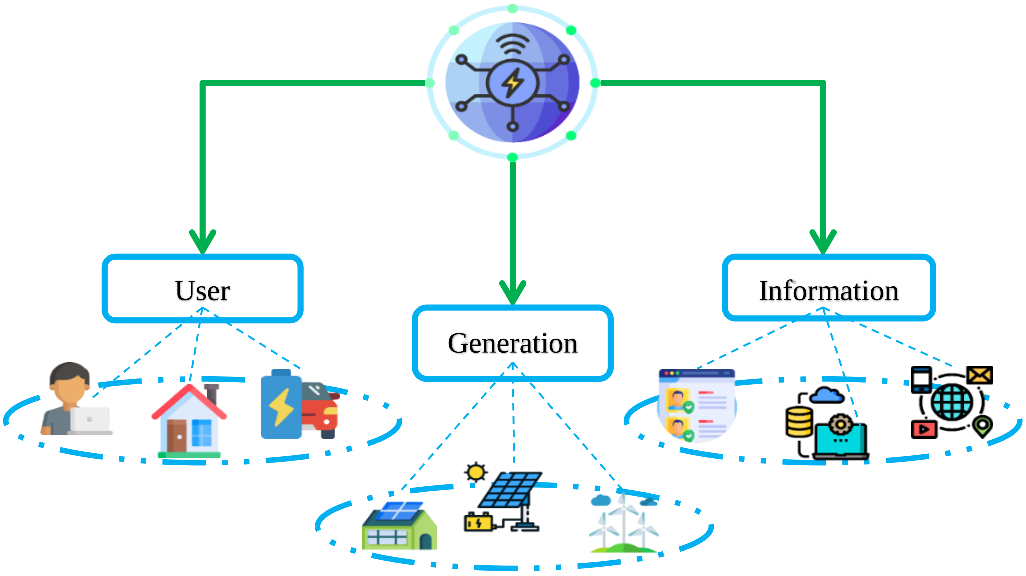

Fig. 1. Energy internet network and its basic components

communication reliability maximization; information security guarantee. These requirements pose significant challenges for data transmission in EI due to its complex structure, heterogeneous components, and dynamic environment [7]. The mismatch between the transmission power of different transmission lines leads to increased energy losses during electricity transmission. To address this issue, some studies [11,12] have proposed a routing planning method for electricity transmission that utilizes multiple paths to optimize the efficiency and reliability of the power grid. However, this method also needs to consider the possibility of transmission line failures due to various factors, such as natural disasters, human errors, or cyberattacks [13].

The modern power system consists of various interconnected components that operate in a coordinated manner. A failure in one component can trigger a cascading effect that propagates throughout the power system network and leads to a large-scale power outage. Such an outage can have serious economic and social consequences for the affected regions and sectors.

This paper proposes a routing algorithm that addresses the challenges discussed above by applying graph theory and probability concepts. The proposed model incorporates the realistic situation by assigning a load value to each power transmission line, which is assumed to follow a normal distribution. Moreover, to account for random errors, the model assumes that all devices and transmission lines are operating within their useful lifespan, and uses an exponential distribution.

Evaluation index, a description of the system, and operational strategies

The evaluation index system is a process that comprises multiple evaluation indices to measure the compatibility of the system. Each index in the evaluation system is employed to quantify the system's attributes and construct a comprehensive representation of the system. Consequently, each index can evaluate each of the properties of the local EI and provide a detailed overview of the network. The validity and reliability of the evaluation system in the local EI can be ensured by the scientific and credit validity of the indices. Therefore, the selection of the indices follows a specific principle [13].

a) **Comprehensive and concise**. The assessment system must contain essential content to achieve the evaluation's goals and accurately reflect the evaluation subject's information.
b) **Independent**. Each index should be generally independent of other indices at the same level.
c) **Representative**. Each index needs to be quantifiable as well as being able to fully capture the characteristics of the research subject.
d) **Comparable**. The index should have a clear distinction for comparison purposes.
e) **Feasible**. The index data should be precise and easy to collect and use.

As presented in Fig. 2, in order to fully and effectively evaluate the local EI, the indices are divided into three aspects: energy, economy, and network-system. In addition, local EI is divided into 9 indices [14]. Indices introduced in the field of energy: loss of load expectation (LOLE), expected energy not served (EENS), and availability. In the economic field, indices are examined based on the significance of the device in the system and in terms of risk, which include two indices of risk reduction worth (RRW) and risk achievement worth (RAW) and importance measurement indices. To assess the reliability of the

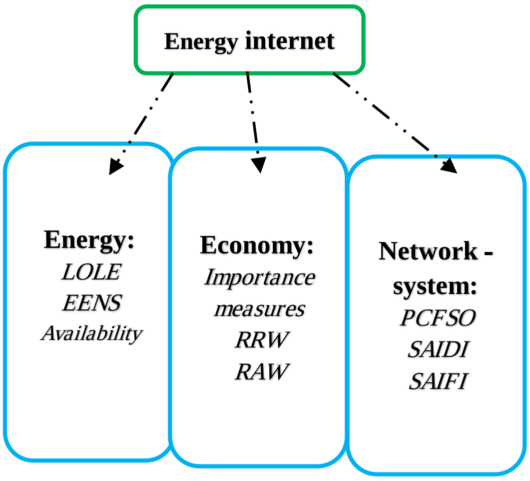

Fig. 2. Reliability evaluation indices by topic

network and system, the indices of the probability of component failure and system outage (PCFSO), system average interruption duration index (SAIDI), and system average interruption frequency index (SAIFI) have been suggested. The EI can be conceptualized as a community-scale power grid where local energy sources, storage, and loads are connected to the grid through Energy Routers (ER). Due to the network topology, the EI is typically modeled as a graph for analysis. Fig. 3 depicts an illustration of a directed graph $G = (V, E, W)$ that represents an IEEE 9-Bus EI. each node v_i stands for an ER or an MG and the edges $e_{ij} = (v_i, v_j)$ of the graph are transmission lines that link nearby ERs or microgrids. The weight of the edge w_{ij} represents the transmission losses brought on by the transmission line resistances, and the direction of the edges indicates the direction of power flow in the transmission lines [18].

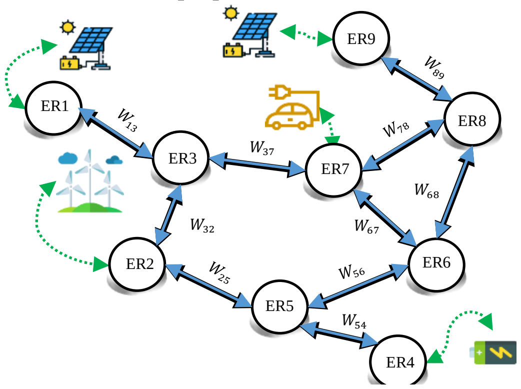

Fig. 3. A local EI topology of IEEE 9-Bus system

Failure modeling

Failure modeling is discussed in this article using two analytical techniques and the Monte Carlo simulation:

1. **Analysis of power transmission line failure in local EI using the analytical approach**

In the EI network, the energy demand node and the supplier are connected by different paths. Paths between two supplier and demand nodes include power transmission lines and ERs that include supply and demand (s, d) path. there are three possible failure scenarios in the case of transmitting power. The first is if transmission power exceeds e_{ij} capacity, the second is when transmission loss surpasses a particular value and the third occurs when a random failure happens along the path as the equipment is in its useful-life period. Markov model is used to model the failure of each path. In this way, first, the reliability block diagram for the existing paths is determined (Fig. 4), then the failure and repair rate are calculated for each state and the probability of each state is determined by the Markov model. The Markov chain for the system states is given in Fig. 5.

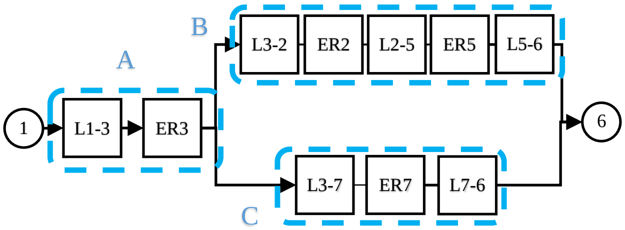

Fig. 4. Reliability block diagram for paths between node 1 and 6

In the Markov model, the limiting probability vector of the states is obtained from the multiplication of the transpose matrix of the limiting probability vector and the stochastic transitional probability matrix, in which Eq. (1) represents the same expression.

$$S^T . A = S^T \quad (1)$$

where S is the limiting probability vector and A is the stochastic transitional probability matrix [15].

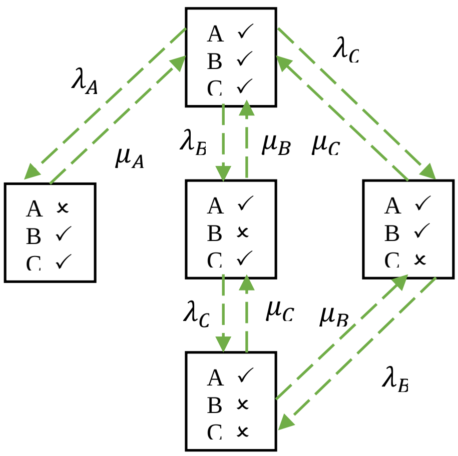

Fig. 5. State space diagram for three devices A, B and C

2. Failure analysis of power transmission lines in the local EI employing Monte Carlo simulation

Path selection is influenced not only by the resistance of the power transmission lines but also by the quantity of electrical power available in the power links and the load power. According to these explanations, the following routing algorithm has been employed focused on maximizing the reliability.

$$argmax_{p\in P}\ Pr(L_s \le L_0\ and\ \lambda_{state} = 1\ ) \quad (2)$$

Where P is a set of possible paths, L_s is total power loss along a path p, L_0 is a parameter that indicates the upper limit of power loss, and λ_{state} shows the state of the path.

$$L_s = \sum_{k}^{N} \left(\sum W_i + \sum W_{ij}\right)_{ks} \quad (3)$$

$$(W_i)_{ks} = (1-\eta_i)P_{ks} \quad (4)$$

$$\left(W_{ij}\right)_{ks} = \frac{R_{ij}}{V_{ij}^2}\left[\left(P_{ks}+P_{-ks}+P_{ex,ij}\right)^2 - {P_{ex,ij}}^2\right] \times \frac{P_{ks}}{P_{ks}+P_{-ks}} \quad (5)$$

Where $\sum_k^N\left(\sum W_i + \sum W_{ij}\right)_{ks}$ represents the transmission loss connected to the kth path, which is the total of the losses of all transmission lines $\sum W_{ij}$ and the power conversion losses of all ERs $\sum W_i$ that make up the kth path. η_i is the conversion efficiency of ER_i and P_k is the power dispatched on the kth path, R_{ij} and V_{ij} are the resistance and voltage of the transmission line connecting ER_i and ER_j, respectively, and $P_{ex,ij}$ is the existing power on the transmission line before the dispatched power P_{ks} and P_{-ks} are added to it. P_{ks} is the sum of the power transmitted over the other pathways that share the same transmission line, and P_{-ks} is the power transmitted through the kth path (i,j) [12].

The parameter $P_{ex,ij}$ indicates the load of each line, which follows the normal probability density function.

$$P_{ex,ij} = \aleph\left(\mu_{ij},\sigma_{ij}\right) \quad (6)$$

Where μ and σ stand for the mean and standard deviation of the line e_{ij} respectively.

And constraints are represented here:

$$\sum_{ks=1}^{N} P_{ks} = P_{d-s} \quad (7)$$

$$P_{ks} + P_{-ks} + P_{ex,ij} \le min\left(P_{ij,cap}, P_{i,cap}, P_{j,cap}\right) \quad (8)$$

$$P_{ks} \ge 0 \quad (9)$$

$$\lambda_{state} = \prod \lambda_{ij} = 1 \quad (10)$$

Where P_{d-s} is the total power transmitted between the source and the sink. The capacities of ER_i, ER_j, and transmission line e_{ij} are $P_{i,cap}$, $P_{j,cap}$ and $P_{ij,cap}$ respectively. Where λ_{ij} shows the state of the line e_{ij} that is whether in normal state 1, or failure state 0. As the lines are in their useful-life period, the random failures follow an exponential distribution.

To evaluate the effectiveness of the optimization process applied to each transmission line, the probability of failure is assessed and the reliability indices defined in the preceding section are calculated. The following mathematical expressions are employed to derive the values of these reliability indices [16], [17]:

$$PCFSO = Pr(D^k > 0\ and\ \lambda_{state} = 0) \quad (11)$$

$$LOLE = \sum_{x=0}^{D} x\,.\,Pr(D = x\ and\ \lambda_{state} = 0) \quad (12)$$

$$EENS = \sum_{i} LOLE_i . T_i \quad (13)$$

$$RRW = \frac{R}{R(\lambda_{ij} = 0)} \quad (14)$$

In these equations, D represents the magnitude of the demand, T denotes the duration of the time interval under investigation, and R signifies the reliability level of the system.

Optimization result and assessment

This section presents the optimization outcomes of the local EI network depicted in Fig. 3. This modeling has been performed using Monte Carlo simulation technique for 10,000 samples. Furthermore, the data pertaining to the network, which comprises the capacities, resistances, and voltage of the lines, is provided in Table 1 and the information regarding the capacity and energy conversion efficiency of routers is also furnished in Table 2. [12].

Table 1. Transmission line parameters

Transmission line	Capacity kW	Resistance Ω	Voltage kV	Load kW
1→ 3	27	0.6	4	μ =15.8 $\sigma = 2$
2→3	21	0.64	4	$\mu = 12.4$ $\sigma = 2.8$
2→5	24	0.51	4	$\mu = 13.7$ $\sigma = 2.5$
3→7	21	0.91	4	$\mu = 12.4$ $\sigma = 1.8$
4→5	28	0.19	4	$\mu = 16.5$ $\sigma = 2$
5→6	25	0.45	4	$\mu = 10.5$ $\sigma = 1.8$
6→7	24	0.24	4	$\mu = 12.2$ $\sigma = 1.3$
6→8	24	0.21	4	$\mu = 15$ $\sigma = 1.8$
7→8	25	0.21	4	$\mu = 14.2$ $\sigma = 2$
8→9	28	0.6	4	$\mu = 12$ $\sigma = 2$

Table 2. ER parameters

ER	Capacity kW	*η*
1	17	0.98
2	25	0.98
3	29	1
4	25	0.98
5	24	1
6	26	1
7	23	1
8	23	0.98
9	22	0.98

In this research case, ER_2 is designated as a supplier node and ER_9 is introduced as a power requester. Based on the optimization process performed to transfer 5 kilowatts of energy from router 2 to router 9, the permissible routes are (2-3-7-8-9), (2-3-7-8-9) (2-5-6-8-9), and (2-5-6-8-9). The failure rate of all the existing transmission lines is assumed to be λ=0.01.

To gain a better understanding of the network under inquiry, three distinct scenarios for the transmission of power have been considered in this analysis. In the first case, only one route is utilized for transmitting power. In the second case, two of the allowed paths carry an equal amount of transmission power. And in the final scenario, 1.25 kW travels along all four paths. The outcomes of this section are presented in Table 3.

Table 3. The results of EI routing analysis for three different scenarios

Scenario 1			
Opt path	**Power transmission kW**	**Power loss kW**	**Probability of failure %**
Path 3	5	0.669	13.23

Scenario 2			
Opt path	**Power transmission kW**	**Power loss kW**	**Probability of failure %**
Path 3	2.5	0.579	4.51
Path 1	2.5	0.564	5.02

Scenario 3			
Opt path	**Power transmission kW**	**Power loss kW**	**Probability of failure %**
Path 3	1.25	0.528	3.68
Path 1	1.25	0.512	4.18
Path 4	1.25	0.512	4.79
Path 2	1.25	0.513	5.05

The results obtained indicate that in the first scenario, the optimal path is the third route, which has a reliability value of 86.77% and a power loss that follows the normal distribution with a mean of 0.699 kW and a standard deviation of 0.091 kW. In the second scenario, the chosen routes are paths three and one, which have reliability values of 95.49% and 94.98%, respectively, and power losses that follow the normal distribution with means of 0.579 and 0.564 kW and standard deviations of 0.1 and 0.11 kW. In the third scenario, all the routes are utilized, and the probability of reliable operation of each route is 96.32% for the third route, 95.82% for the first route, 95.21% for the fourth route, and 94.95% for the second route, according to Table 3, and also the power losses that follow the normal distribution with means of 0.528, 0.512, 0.512, and 0.513 kW and standard deviations of 0.11, 0.11, 0.1, and 0.1 kW are obtained for each route.

The investigation of the PCFSO for power transmission ratios of 0.25 in four paths, 0.5 in two paths, and 1 in one path for transferring 4 to 7 kW is shown in Fig. 6. It should be emphasized that in this comparison if multiple transmission paths are employed, the failure of any one of them will result in the failure of the entire system.

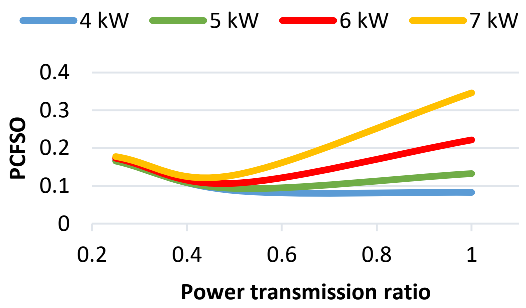

Fig. 6. System failure probability diagram

In the following, this paper employs a combination of analytical techniques and Monte Carlo simulation to calculate LOLE and EENS. These indices are easy to calculate for a single transmission path, but when power is transmitted across multiple paths, the system must be modeled as a parallel system. Fig. 7 illustrates an example of a four-path transmission system.

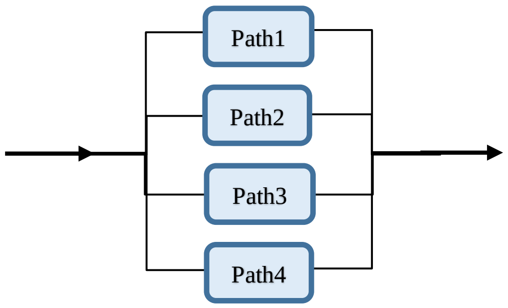

Fig. 7. An example of a four-path transmission

Using data on transmission power and probability, this paper computes this index and presents it in Fig 8.

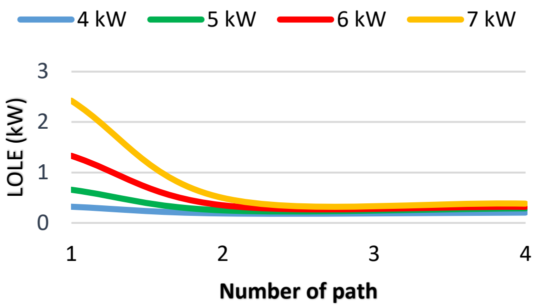

Fig. 8. Diagram of loss of load expectation

This paper also examines one of the economic indices, namely RRW, from an economic perspective. To determine this index, the network is first formulated based on its transmission lines, considering their importance in the path. The routes are reformulated as follows: Path 1 (Line 2-3, Line 3-7, Line 7-8, Line 8-9), Path 2 (Line 2-3, Line 3-6, Line 6-7, Line 7-8, Line 8-9), Path 3 (Line 2-5, Line 5-6, Line 6-7, Line 7-8, Line 8-9) and Path 4 (Line 2-5, Line 5-6, Line 6-8, Line 8-9). In order to estimate the total failure probability and the separate failure probability based on the failure of each line, the network must be decomposed into a series of smaller subsystems using the Cut-set method. This method involves identifying Cut-sets and Incidence matrixes for each subsystem. The results of this procedure are shown in Tables 4 and 5.

Table 4. Incident matrix for power transmission

	Line 2-3	Line 2-5	Line 3-6	Line 3-7	Line 5-6	Line 6-7	Line 6-8	Line 7-8	Line 8-9
Path 1	1	0	0	1	0	0	0	1	1
Path 2	1	0	1	0	0	1	0	1	1
Path 3	0	1	0	0	1	1	0	1	1
Path 4	0	1	0	0	1	0	1	0	1

After decomposing the local EI into a series of smaller subsystems, the calculations are performed using equation 13, which gives the ratio of the system reliability to the reliability of the system when the line e_{ij} fails. This ratio indicates the impact of each line on reducing the risk of the whole system. Based on the results, the transmission line from node 8 to node 9 has the highest value for this ratio, implying that it is the most critical line for maintaining system reliability. The ranking table data for all lines are provided in Table 6.

Table 5. First, second, and third order of minimal cut sets

First order cut sets	Second order cut sets	Third order cut sets
Line 8-9	Line 2-3, Line 2-5 Line 2-3, Line 5-6 Line 2-5, Line 7-8 Line 5-6, Line 7-8 Line 6-8, Line 7-8	Line 2-3, Line 3-6, Line 3-7 Line 2-3, Line 3-7, Line 6-7 Line 2-6, Line 3-6, Line 3-7 Line 2-6, Line 3-7, Line 6-7 Line 2-3, Line 6-7, Line 6-8 Line 2-3, Line 6-8, Line 7-8

The ranking based on RRW enables rational decision-making to minimize risk at the lowest cost. In this example, improving the reliability of the line from node 8 to node 9 has a significant effect on enhancing the reliability of the whole system compared to other lines. This illustrates the importance of measuring engineering systems based on various reliability indices in different categories.

Table 6. Ranking of power transmission lines based on risk reduction worth

Rank	Line	RRW
1	8-9	20.7628
2	7-8	1.0295
3	5-6	1.0196
	2-5	1.0196
	2-3	1.0196
4	6-8	1.0098
5	3-7	1.0004
6	6-7	1.0003
7	3-6	1.0002

Conclusion

The items that have been discussed in this study support the use of appropriate indices that have been stated in accordance with the required characteristics, such as comprehensiveness and simplicity, independence, representativeness, comparability, and feasibility. In the local EI, these characteristics are used to find several reliability indices in three different categories: Energy, Economy, and Network-system.

Failure modeling for the local EI has also been developed using the analytical method and Monte Carlo simulation. In order to obtain suitable results, the model considers the load in the power transmission lines and to make this modeling closer to reality, the normal probability density function has been used for the probability of the load in each line.

Finally, the introduced reliability indices have been calculated, and according to these results, to increase the reliability of the routing network, it is better to use two paths for power transmission. Power transmission from two parallel paths gives an even better result in not losing power through introduced failures. This transfer has been investigated under an equal ratio for both paths, although optimization can be done on the power transfer ratio for two paths in future studies. Economic indices also contribute to the value of the investment and the optimal increase in the reliability of the system is affected by the increase in the reliability of every part of the system.

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