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REVIEW PAPERS

A review of failure rate studies in power distribution networks

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Abstract This article examines the research carried out regarding the failure rate in electricity distribution systems. It introduces a comprehensive framework for managing failure rates in power distribution systems. This framework highlights that studies on failure rates in power distribution systems can be categorized into three distinct groups: modifying asset management activities in order to reduce failure rate, evaluate and control threats and risks, emergency measures after failure. In this article, all the studies conducted on the failure rate of electricity distribution systems are listed and presented, and categorized in the form of a comprehensive and conceptual framework. The relation of each category with the failure rate is explained and by studying the process of studies, the research gaps and the roadmap of future studies in the field of failure rate in electricity distribution systems are determined.

Keywords Failure rate · Power distribution systems · Reliability

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1 Introduction

The failure of assets leads to the ineffectiveness of the assets network and its management system. For this reason, after asset failure, the asset repair procedure must be started quickly so that the asset, network, and system return to their normal state. In addition to the costs of the exclusion from the sale of energy and the replacement of the damaged property, the costs of fixing the defects are the need to hire and use human resources, tools, and machines to fix the defects of the assets. The imposed cost due to asset failure is not only related to the electricity distribution industry and energy industries, but this imposed cost exists in all industries; So that in all industries, failure rate is one of the important criteria for investment in asset management and current budget allocation (opex). The value of the failure rate determines the amount of the imposed cost, and the asset protection solutions and reduction of the failure rate are the criteria for determining the amount of investment.

The electricity distribution system has different characteristics compared to other systems and industries. Because electricity distribution systems have a continuous and daily development process to supply electricity to branch applicants. For this reason, the diverse number of assets in different lifetimes and diverse failure rates are the main characteristics of the electricity distribution system. These characteristics cause different behavior in the failure rate in the network and electricity distribution system compared to the failure rate of assets.

In risk studies, the failure rate is modeled by the bathtub curve. In risk studies, failure rate modeling is done by bathtub curve. Electricity distribution networks consist of different assets with different lives and failure rates, so the bathtub curve becomes a constant value per year and of course variable in successive years.Because the operating time of the assets of the electricity distribution system is high in the bathtub curve, the fluctuating effects of the origin and aging time are eliminated by the multiplicity of assets with different lifetimes.

The failure rate can be used to plan investment, development, and elimination of wear and tear and to plan the operation of electricity distribution system assets. For this purpose, the following 5 items are required in the field of electricity distribution system failure rate:

- *Failure rate planning*: Failure rate planning includes economic planning and cost–benefit studies of activities that affect the failure rate. By planning and prioritizing actions, the failure rate can be reduced.
- In addition to economic goals, failure rate planning has another goal, which is to maintain and improve the stability of the electricity distribution system. An increase in the failure rate causes severe customer dissatisfaction, an increase in fines, and as a result, the instability of distribution management from an economic point of view and the point of view of service provision.
- In addition to the above-mentioned cases, actions after property damage require structure and infrastructure planning.
- *Monitoring and evaluation*: Every planning requires two key monitoring:
- Monitoring of planned indicators
- Monitoring the planned activities to ensure that they are done correctly and accurately
- The aforementioned monitoring and evaluations can identify and introduce deviations from the plan and the factors causing these deviations so that in case of control, programs can be implemented better or planning defects can be identified.
- *Control and correction*: The conducted monitoring shows the effectiveness of the programs and the methods of improving the failure rate. Knowing about the efficiency of the programs and the factors affecting them should be applied in the form of planning modification so that the failure rate can be controlled. Failure to make corrections based on the results of monitoring causes the lack of proper acceleration in the improvement of the failure rate of the electricity distribution system.
- *Coordination of plans and actions*: creating coordination between the actions of the management system creates capability and increases the efficiency of actions to achieve management goals and failure rate control programs.
- *Organization of resources, human resources, and facilities*: carrying out failure rate management programs in electricity distribution systems requires the organization of human resources, resources, and facilities to guarantee the implementation of measures in the form of a suitable structure and procedure.

The above-mentioned items are key indicators of management. For this purpose, failure rate management in electricity distribution systems should be the main criterion for conducting failure rate studies. To date, numerous fragmented studies have explored the failure rate in power distribution systems. However, these studies fail to encompass all aspects of failure rate management, highlighting the existing gap and the necessity for further research in the field of power distribution system failure rates.

This paper presents a comprehensive model for managing failure rates in power distribution systems and presents conceptual models to understand the location of failure rate in electricity distribution networks and has reviewed previous studies in this field.

The model proposed in this article aims to incorporate all the existing studies on power distribution system failure rates and provide a framework for managing these rates, thereby identifying research gaps in the field. The second section of the article focuses on highlighting the distinctions between electricity distribution systems and other systems concerning failure rates. The third section explores the applications of failure rates in electricity distribution studies, while the fourth section examines the impact of risks and threats on failure rates. The fifth section discusses the utilization of failure rates in asset management, and finally, the sixth section addresses emergency response plans in the event of failures.

2 The location of failure in studies of electricity distribution systems

The asset failure rate index shows the quality of service expected from that asset. Failure factors are divided into three independent categories:

2.1 Managing the development and installation of assets

Lack of proper development planning for proper loading of assets, as well as lack of production or correct installation of assets in the network, increases the breakdown of assets and reduces their life.

2.2 Threats and factors causing damage to assets

Factors such as natural disasters (HILP) or hostile threats or risk factors such as people's behavior with assets or car accidents etc. all cause asset damage. The dependence of assets and services of the power distribution system on the health and performance of other assets and services makes this system vulnerable to the reliability of that system and threats that disable the system in question.

2.3 Lack of optimal management of existing assets

Every asset should be optimally subjected to repairs and other asset management measures to achieve its pre-designed useful life. Failure to properly and accurately perform asset management activities reduces the asset's useful life and increases the rate of failure. Asset management activities include various activities that result in the maximum productivity of the asset with the lowest cost.

Thus, one of the important factors affecting the failure rate and its reduction is the complete and quality performance of asset management activities. Figure 1 shows the failure rate diagram for each asset. The top three blocks are crash factors that cause crash mods in each asset. On the other hand, there are different failure modes according to the asset type, so the asset type block is mutually related to the failure mode, which ultimately forms the failure rate for each asset.

So far, several studies have been conducted in the field of failure factors and modes, which can be summarized in Table 1. (Fig. 2)

As it can be seen from Table 1, in the area of failure factors and modes, the most studies have been done in Asset Type and the least in Asset Boring, which should be included in the roadmap for future studies.

3 The application of the failure rate index in studies of electricity distribution systems processes

The derived failure rate can be employed across multiple applications within power distribution systems to analyze

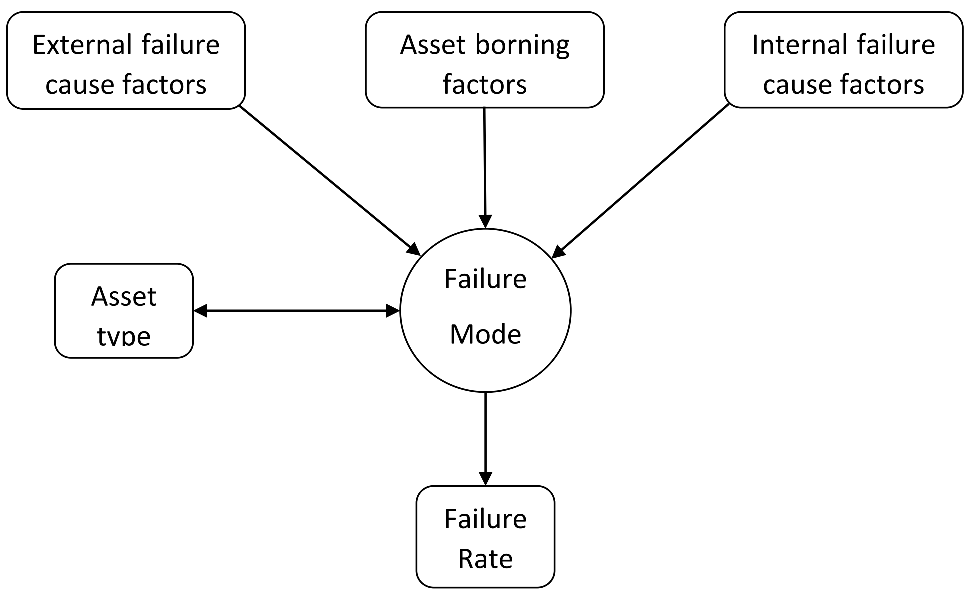


Fig. 1 Failure factors and modes in power distribution systems

Table 1 Classification of studies conducted in the field of failure factors and modes in electricity distribution systems

Asset type	Abbasi and Malik 2016; Aizpurua et al. 2018; Ghasemi et al. 2023; Gilvanejad et al. 2017; Gupta et al. 2005; Haghifam et al. 2009a; Horton et al. 1990; Jürgensen et al. 2019; Arulraj and Kumarappan 2019; Brown 2004; Bucci et al. 1994; Aj. Christina et al. 2018; Dumitran et al. 2014; Etumi and Anayi 2016; Farag et al. 1998; Farajollahi et al. 2018)
External failure cause factors	Etumi and Anayi 2016; Alizadeh et al. 2021; Bertling et al. 2002; Ekstedt and Hilber 2014; Pan et al. 2009; Sahai and Pahwa 2006)
Internal failure cause factors	Etumi and Anayi 2016; Alizadeh et al. 2021; Bertling et al. 2002; Ekstedt and Hilber 2014; Pahwa and "Modeling weather-related failures of overhead distribution lines", in 2007)
Asset borning factors	–
Failure mode	Aizpurua et al. 2018; Akula et al. 2022; Pourramazan et al. 2007; Saraswati et al. 2014; Singh et al. 2019; Amare et al. 2018; Baleia 2018; Beshir 1989; Chu et al. 2010; Enjavimadar and Rastegar 2022; Enjavimadar and Rastegar 2022; Li et al. 2022; Liu et al. 2013; Pinna et al. 1998)

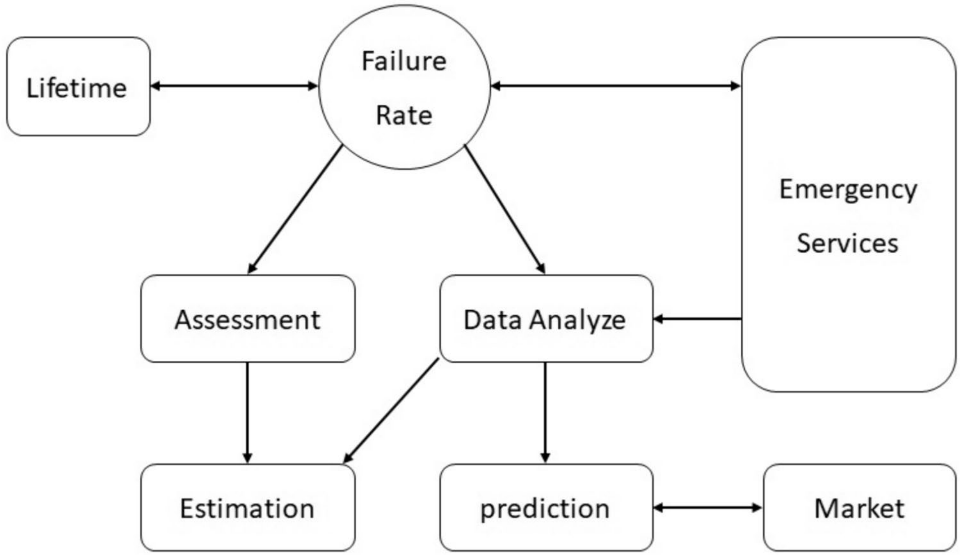


Fig. 2 Applications of failure rate in power distribution systems

and enhance the efficiency of their processes. The applications of the failure rate can be categorized as follows:

- Predicting the state of the system, network, and assets to perform asset management activities optimally.
- Assessment and estimation of the state of assets against all kinds of threats and risks: with the help of this estimation, preparations can be made to eliminate the consequences and manage the crisis.
- Estimating the life of assets for network planning and studies and economic planning of electricity distribution systems: including economic studies of electricity distribution systems, it is possible to plan assets on the network in investments, tariff policies, and The total price of electricity distribution services is mentioned. The asset deterioration rate is effective in all investment activities and optimization cannot be achieved without considering it.
- Emergency response planning for property damage and power distribution network outages.

By causing a failure in the assets of the power distribution system or blackout of the subscribers of the emergency service groups (ERP), which includes troubleshooting teams and blackout management as well as crisis management, they are on standby to restore the network by carrying out repairs and load recovery. Or use alternative methods to normalize the network. The most important pillar in this department is the operator, which includes monitoring, data analysis, team management, and an automation system. Vasil operator is the interface of property and business management and can take measures based on cost-effectiveness. One of the key features of the operator is the use of MG, DER, REN, and smart network capacities. which has been investigated in various studies on the failure rate in the presence of one of the above cases.

According to the stated contents, the applications of the failure rate can be drawn as Fig. 3:

Blocks that represent a process are connected with each other and two-way arrows are placed between them in the figure.

To date, numerous research studies have explored the applications of failure rates in electricity distribution systems, which are summarized in Table 2.

As can be seen from Table 2, in the field of failure rate applications in electricity distribution systems, most studies have been done in lifetime and assessment but the least in market scope, which should be included in the roadmap for future studies.

In this way, the general scheme of failure rate management can be influenced as Fig. 4. The important point in this form is to know the internal failure and external failure components

4 Threats to asset management of electricity distribution system:

As stated before, one of the most important factors in the failure rate of electricity distribution system assets is the threats to these assets. Threats to the power distribution system can be divided into four main categories:

Table 2 Classification of studies conducted in the field of failure rate applications in electricity distribution systems

Lifetime	Aizpurua et al. 2018; Dumitran et al. 2014; Zhang et al. 2006; Zhao et al. 2014; Biçen et al. 2014; Fogliatto et al. 2022; Foros and Istad 2020; Hong et al. 2009; Islam et al. 2018; Maximov et al. 2018; Wang et al. 2014; Ye et al. 2018)
Assessment	Saraswati et al. 2014; Asgarpoor and Mathine 1997; Moon et al. 2004; Peyghami et al. 2019; Zhang and Gockenbach 2007; Awadalla et al. 2015; Chen et al. 2005; Corotis et al. 2020; Duan et al. 2011a; Jürgensen et al. 2017; Jürgensen et al. 2016a; Jürgensen et al. 2018; Louit et al. 2009)
Data analyze	Adoghe et al. 2013; Afsharinejad et al. 2021; Haghifam et al. 2009b; Hamza et al. 2019; Jürgensen 2016; Prasad and Rao 2003) (Zhang et al. 2004)
Prediction	Aizpurua et al. 2018; Bucci et al. 1994; Hong et al. 2009; Roberts and Mann 1993; Cochenour et al. 2008; Du et al. 2020; Fang et al. 2022; Kabir et al. 2015; Kjølle and Holen 1998; Li, et al. 2019; Radmer et al. 2002)
Market	Arulraj and Kumarappan 2019; Kjølle and Holen 1998; Moghimi et al. 2020)
Estimation	Abbasi and Malik 2016; Gilvanejad et al. 2017; Yang et al. 2016; Moon et al. 2007; Moon et al. 2005; Clavijo-Blanco and Rosendo-Macías 2020; Doostan et al. 2017; Gilvanejad et al. 2013; Jürgensen et al. 2016b; Liang et al. 2012; Moradkhani et al. 2014a; Moradkhani et al. 2015; Moradkhani et al. 2014b)
calculation and failure modeling	Jürgensen 2016; Horton and Goldberg 1991; Huang et al. 2020; Jürgensen 2018; Moon et al. 2006; Pahwa 2004; Pathak et al. 2006; Pylvänäinen et al. 2005; Qiu et al. 2015; Taghi Tahooneh and Dashti 2022)

4.1 HILP

Natural hazards are said to have a very low probability and a very high impact, such as earthquakes, storms, tsunamis, dust storms, etc.. This category of threats arises with the change in climate conditions. Global warming plays a key role in increasing these risks. In most HILP incidents, a large portion of assets is physically damaged. The important point in this threat is the dependence of the consequences on Planning, that no asset should be designed and created at the location of HILP, if possible.

4.2 Risk cause failure factors

Several factors have a destructive effect on the assets of electricity distribution systems. These factors show their effects over time. Risk factors have various effects in different geographical areas. In addition, unforeseen events such as human error, theft, car accident, etc. It increases the failure rate.

4.3 Dependence of infrastructures on each other

This category of threats is caused by the vulnerability of other infrastructures. Applying risks and threats to other infrastructures can lead to property damage or shutdown in case of dependence.

The set of external factors affecting the failure rate can be shown in Fig. 5.

So far, several studies have been conducted in the field of effective external factors, which can be summarized in Table 3.

The review of studies shows that there have been good studies in the field of external factors in HILP accidents and infrastructures interdepency, but no study has been found in the critical areas related to the failure rate.

5 Asset management failure rate (AMFR)

Asset failure is measured by incorrect production and construction of assets and external threats to the system, and it is also measured by the non-optimal performance of asset management activities, which we call AMFR. Asset management activities in electricity distribution systems can be summarized as follows:

- *Protection management*: In this category of measures, electricity distribution assets are protected from risk factors with the help of relays and fuses. This procedure conflicts with system reliability and requires compromise.
- *Load management*: Assets must be continuously monitored, and if the load does not match the capacity, the capacity or load must be modified with the help of capacity building, consumption management, changing the feeding route, or using DER. Failure to properly manage the load and productivity of assets beyond their capacity will cause damage to them.

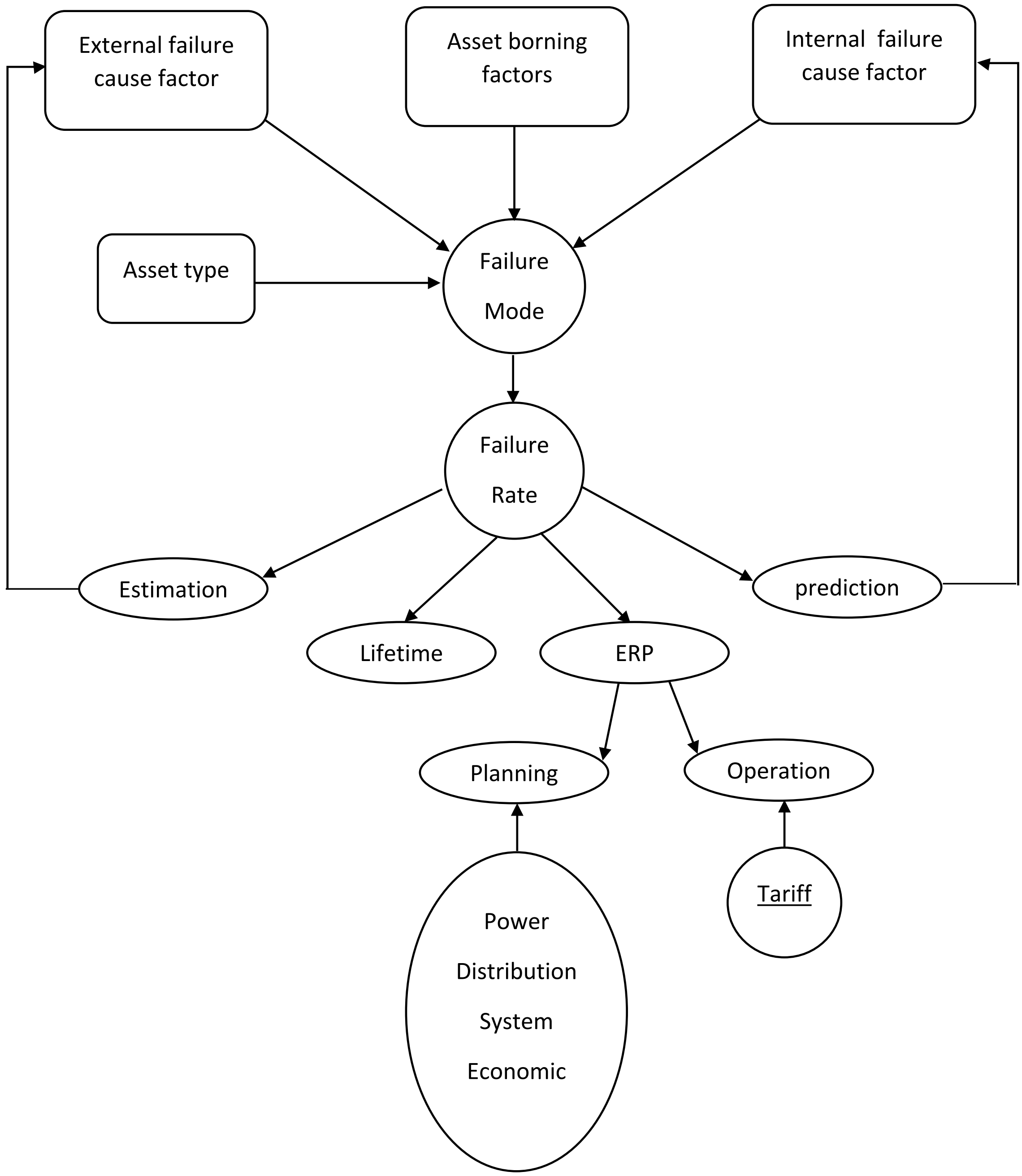


Fig. 3 Failure rate framework in power distribution systems

- *Management of repairs*: in this procedure, plans, monitors and optimizes visit and service activities and fixes asset defects. If repairs are carried out optimally and completely and on time, the probability of failure will be minimized, but due to the high quantity of assets and the high resilience of assets, this procedure is practically limited by managers and investors, which itself hurts the rate of asset failure.
- *Management of worn-out assets*: As the assets wear out, their defects increase, and the failure rate increases. Early replacement of worn-out assets is not economical. Because of this, the replacement time is determined by the trade-off between the lost cost and the necessary expenditure. The average failure rate of the network and system is determined by the time it takes to replace worn-out components. Even if worn-out assets deteriorate at

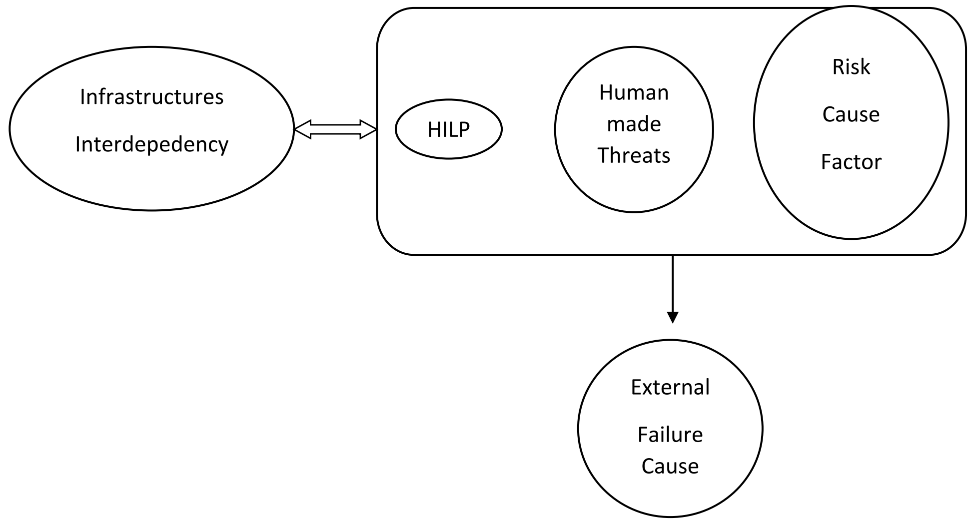


Fig. 4 Threats and external factors affecting the breakdown of electricity distribution systems

Table 3 Classification of studies conducted in the field of external factors affecting failure rates in electricity distribution systems

Infrastructures interdependency	Amare et al. 2018; Corotis et al. 2020; Chai et al. 2016; Cheng et al. 2009; Chu et al. 2009)
HILP	Sahai and Pahwa 2006; Du et al. 2020; Chaudhuri et al. 2012; Yang et al. 2019; Zúñiga et al. 2020)
Human-made threats	–
Risk cause factor	–

a rapid pace, how they are handled and maintained may significantly slow down the rate of degradation. Because of this, the method of managing worn-out assets in terms of the activities of the aforementioned clauses has a significant influence on the amount of asset degradation rate in addition to the timing of asset replacement.

- *Reinforcement and protection of assets*: Electricity distribution assets are vulnerable to various natural hazards and threats. Rehabilitating assets reduces their damage rate during accidents. At the time of accidents, risks, and threats, not all assets are damaged, but in some of them, the potential for defects is created, and after the crisis is resolved, it shows itself in the form of an increase in the rate of failure. Rehabilitating assets reduces the rate of failure after the crisis caused by risks and threats is resolved.

It can be seen that the non-optimal performance of asset management activities and measures increases the failure rate in electricity distribution systems. The effectiveness model of the failure rate of asset management activities can be shown in Fig. 6.

So far, several studies have been conducted on the impact of asset management activities on failure rates, which can be summarized in Table 4.

As it can be seen from Table 4, in the area of the impact of asset management activities on the failure rate, most studies have been done in maintenance management and few studies have been done in protection management and test sections, which should be included in the roadmap of future studies.

6 Emergency response plan (ERP)

The emergency response is activated after an error occurs in the network and equipment failure. The emergency response of the system can include one incident, several simultaneous but independent incidents, or cascading. Most simultaneous outages occur when HILP events are the cause of failure. In incidents with the low consequences, a blackout management procedure (OEM) is implemented, but in incidents or large and simultaneous consequences, crisis management (CRM) is activated. In both OEM and CRM procedures, after informing about the incident and dispatching the crew, the faulty network is isolated and the maximum time when the power supply path is not faulty, it is restored with the help of the alternative power supply path or by using DG or REN.

In this regard, if there is a need to implement DR programs, it will be possible so as not to lead to force shutdown

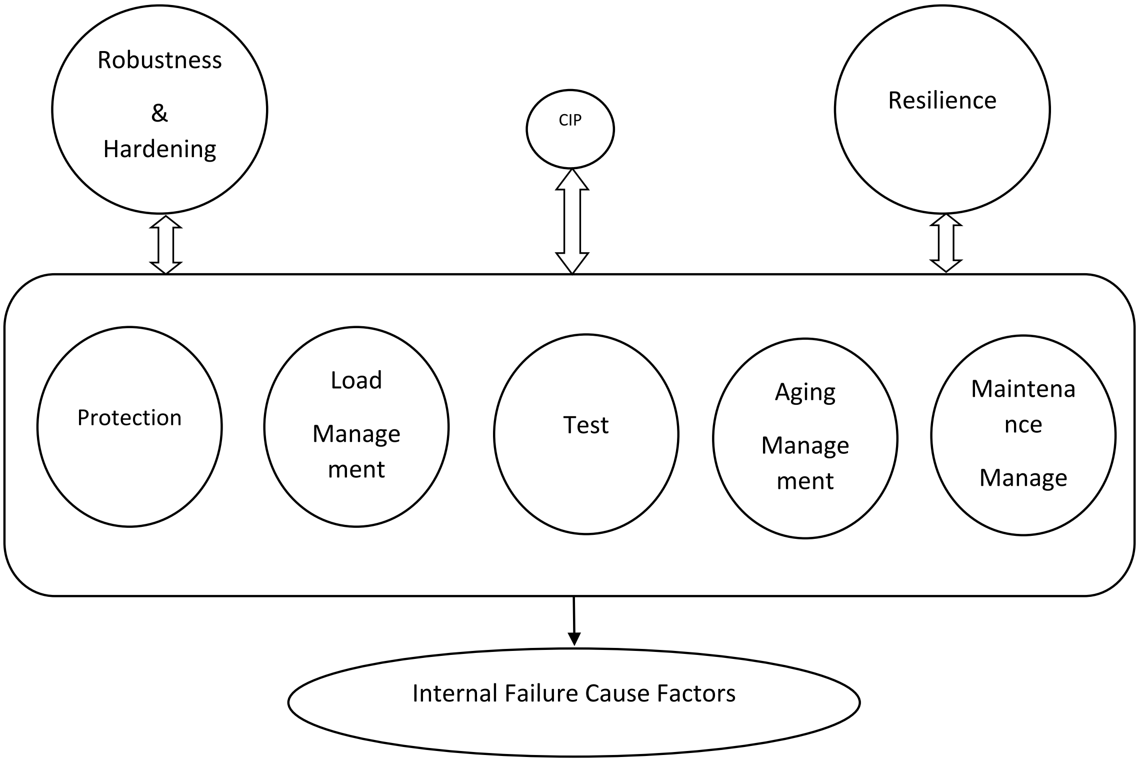


Fig. 5 Effectiveness model of failure rate from asset management activities

Table 4 Classification of studies conducted on the impact of asset management activities on failure rates in systems

Robustness and hardening	Hashemi et al. 2010; Koç et al. 2013; Yang et al. 2021)
CIP	Liu et al. 2022; Hamzeh and Vahidi 2022)
Resilience	Afsharinejad et al. 2021; Chai et al. 2016; Hassett et al. 1995)
Protection management	Wang et al. 2011)
Load management	Biçen et al. 2014; Gilvanejad et al. 2013; Alam et al. 2016; Filus 1987; Rahmani-Andebili 2015; Velotto 2011)
Maintenance management	Alizadeh et al. 2021; Bertling et al. 2002; Enjavimadar and Rastegar 2022; Louit et al. 2009; Adoghe et al. 2013; Chu et al. 2009; Hajivand et al. 2019; Jiang 2006; Kumar et al. 1999; Roos and Lindah 2004; Shariffuddin, et al. 2022; Teera-achariyakul and Rerkpreedapong 2022; Alkali et al. 2009; Belyi et al. 2017; Bertling et al. 2005; Dezaki et al. 2013)
Test	Islam et al. 2018)
Aging management	Awadalla et al. 2015; Duan et al. 2011a; Li, et al. 2019; Jianquan et al. 2014; Li 2002)

or load shedding. Of course, the facilities used in OEM and CRM can also be used to manage the load and reduce the failure rate.

Then the repair teams are sent to fix the problem and after the problem is fixed, the network is normalized. All the mentioned steps should be managed by the operating system to maintain the safety and stability of the network. For this reason, the operator, its requirements, and its functions play a key and vital role in the emergency response to asset damage.

The most important part of the operator is data monitoring and its analysis, so that the state of assets, network, and the system can be predicted and estimated, and the possibility of assessing the state of asset management or system threats can be provided. From this possibility, it is possible to reduce the failure rate by optimizing asset management activities or preparing against threats to preserve assets.

It can be seen that a large part of the failure rate management and its reduction goes back to the operator and emergency response to take action to reduce the failure rate in

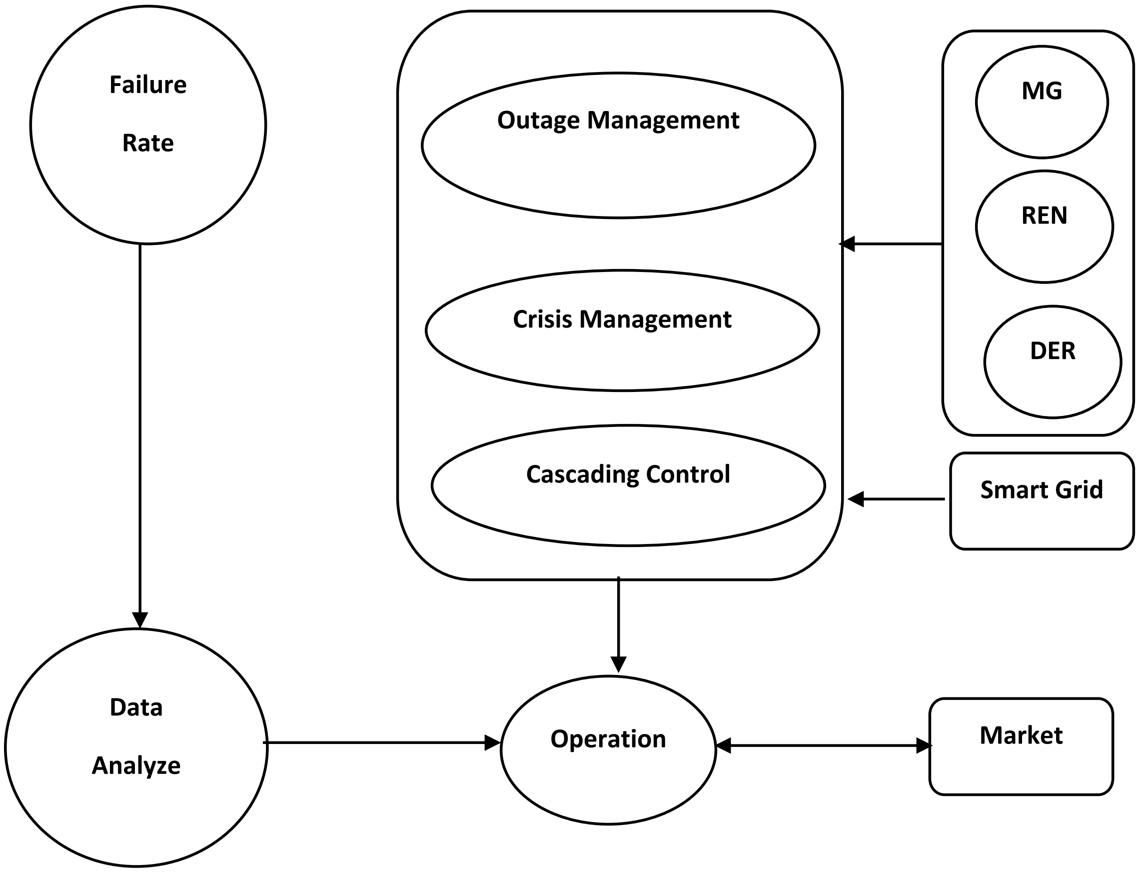


Fig. 6 ERP model and failure of electricity distribution systems

Table 5 Classification of studies conducted in the field of ERP model after failure in electricity distribution systems

Outage management	Arif et al. 2017; Bhavaraju et al. 1985)
DER and MG	Wu et al. 2022; Perrier et al. 2013)
Operation	Kumar et al. 1999; Dezaki et al. 2013; Duan et al. 2011b; Sun et al. 2010; Takahashi 2022)
Cascading control	Chai et al. 2016; Koç et al. 2013; Azzolin et al. 2018; Bao et al. 2009; Cordova-Garcia et al. 2018; Fan and Liu 2013; Frasca and Gambuzza 2021; Kinney et al. 2005)
Smart grid	Aizpurua et al. 2018; Akula et al. 2022; Amare et al. 2018; Baleia 2018)
Crisis management	Dent et al. 2011)

the future by receiving feedback and in addition to prevent failure by preparing for natural hazards and threats. With a good ERP and a suitable and optimal operator, it is possible to prevent the destruction of assets during the repair of an asset or the removal of a blackout.

The ERP model that is activated after a failure can be displayed as follows:

So far, several studies have been conducted in the field of ERP model after failure, which can be summarized in Table 5.

As it can be seen from Table 5, in the field of ERP model after the failure, the most study has been done in Cascading Control and the least study in Crisis Management, which should be included in the roadmap of future studies. Of course, many studies have been conducted in the field crisis management, but it is not related to the breakdown of electricity distribution systems.

7 Conclusion

As seen in the previous sections, failure rate management starts before the accident and continues until after the

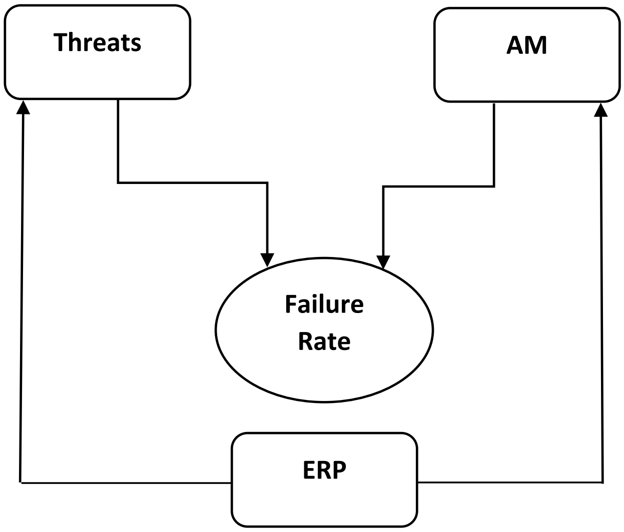


Fig. 7 Failure rate management in power distribution systems

failure, and has a closed management loop that can be displayed as follows:

Figure 7, which shows the failure rate management model, can be called the failure rate butterfly model, which shows:

1. The management and reduction of the failure rate start before the accident and continues until the repair of the defect, failure, and blackout.
2. To reduce the failure rate, in addition to receiving feedback and improving asset management, it is necessary to evaluate threats and prepare for them.

Table 6 General classification of studies conducted in the field of failure rate in electricity distribution systems

The most subject of studies	Number of papers	
HILP	10	AM
Maintenance Management	31	Threats
Cascading control	22	ERP

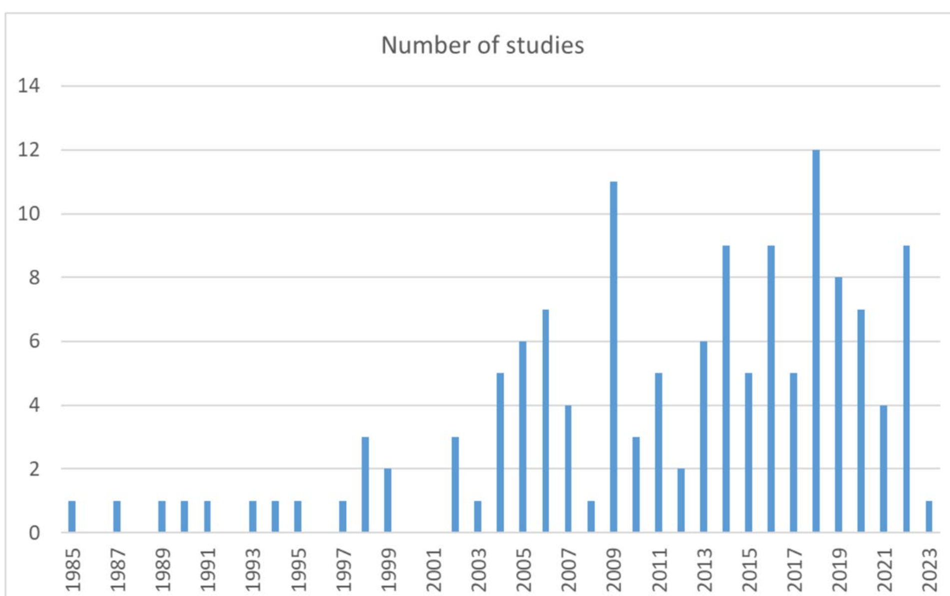
By summarizing the studies conducted in the field of the failure rate of electricity distribution systems, the number of studies conducted each year can be obtained in the form of the Fig. 8.

By reviewing and summarizing the statistics of the studies, we arrive at the following table: (Table 6)

Among the cases that have received less attention so far in the field of failure rate and can be included in the roadmap of future studies of failure rate management in electricity distribution systems can be mentioned as follows:

- Identifying and measuring the effective factors of ERP on the failure rate of electricity distribution systems
- The effectiveness of the failure rate of each asset management activity in electricity distribution systems
- Effectiveness of the failure rate from each of the risk and threat factors in electricity distribution systems
- Forecasting and planning management of failure rate in electricity distribution systems

Fig. 8 The process of conducting failure rate studies in electricity distribution systems



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Declarations

Conflict of interest The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript. The authors whose names are listed immediately below report the following details of affiliation or involvement in an organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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