Fuzzy Inference-Based Safety Monitoring Framework for Substation Power Operation Sites Using IoT Sensor Networks

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An important aspect of the country's power supply is the infrastructure development of the power grid. There are a lot of people and pieces of machinery involved in power building, and it often involves teams from several industries working together. As a result, SPOS (substation power operation safety) safety management is notoriously difficult to attain. An enhanced security administration and oversight system based on the IoT with smart sensors is suggested and implemented to enhance the safety management with control of SPOS. An examination of the safety management system's building process is conducted according to the SPOS's characteristics. Intelligent sensors collect data on operational parameters, which are then sent by means of industrial gateways and Internet of Things connectivity devices. The BIM map would display the outcomes of the analysis carried out through artificial intelligence algorithms on the monitoring data. At long last, a control and management system that includes monitoring, early warning, and alarms has been built. In SPOS's safety control and administration section, the topic of smart construction site solutions is also covered. When used in conjunction with the real field system, it confirms that the safety control and management system is reasonable. Operators can make better, more proactive choices about maintenance and resource allocation because to the continual nature of the output. An example would be giving more priority to a substation with a risk index of 0.85 than one with an index of 0.65, even though both would be deemed "high risk" according to the conventional approach. Compared to previous models, this one has a greater prediction accuracy (96 percent), can appropriately produce signals of varying levels, and may serve as a reference for the development of substation safety warning, preventive, and control systems in the future.

Povzetek: Predstavljen je varnostni nadzorni okvir za elektroenergetska razdelilna mesta, ki združuje IoT senzorska omrežja in mehko logiko. Sistem omogoča sprotno ocenjevanje tveganj, zgodnje opozarjanje in večnivojsko odločanje za izboljšano varnost in zanesljivost obratovanja.

1 Introduction

Substations provide a safe haven for power circuit switching and, in certain cases, voltage conversion. In this context, "substation" means both substations along with switching stations. Due to the fact that substation equipment is often only partially deenergized for maintenance [1], [2], substations provide an inherent safety risk. An in-depth familiarity with the substation, including its aerial and subsurface line connections, is essential for the safe operation along with upkeep of the system. When cared for correctly, systems are built to be secure to use. Maintaining a safe working environment requires familiarity of the work dimension, its dangers, and its design foundation in order to do maintenance in a way that avoids risks. The (n-1) safety criteria are used for the sizing of certain electrical components in power plants along with substations, whereas the (n-2) criterion is used in nuclear power plants [3], [4]. According to the concept, safety of the grid must be ensured in the event that a component, such a transformer or circuit, is disabled or fails in an electrical grid that is expected to handle maximum transmission and distribution jobs. The installation's monitoring technology has a unique problem due to the electrical systems' ensuing redundant nature. Operators may analyze system data as per their requirements, use it to enhance the system, and establish correlations between measurement data and other power plant occurrences. This is useful for identifying the origins of temporary insulation problems, as repair crews aren't always able to respond to fault notifications in a timely manner (within a few hours), pinpoint their exact location, and remove them.

The electric traction power supply network has two modes of operation: normal and fault. Failures in the contact line, substation posts, or traction substations may lead to the fault regime [5], [6]. Several forms of electrical traction-specific protection safeguard power supply system electrical equipment against aberrant operating regimes. Commissioning protective relays in power system security applications involves using a relay test equipment to measure the operating time of the relays and the states of the breakers during various electrical failures [7], [8]. Afterwards, it would be possible to build up overcurrent protective relays to provide inverse time overcurrent security, and then compare the estimated and measured timings of the relays. Additionally, it is possible to assess the selectivity coordination of the main and backup protection systems [9], [10]. For main and backup protection, relay-relay devices should have a measured minimum CTI of more than 7.2 cycles, and fuse-relay devices should have a measured minimum CTI of more than 12.2 cycles. For various power grid applications, Table 1 details the % error with minimum CTI limitations [11], [12], [13].Table 1 illustrates the Power grid applications requiring minimal CTI restrictions and measurement percentage error.

Table 1: Power grid applications requiring minimal CTI restrictions and measurement percentage error

Type of Simulation	**Measurement Applications at Electrical Substations and Power Grids**		**Percentage Error and Minimum CTI Limits**
Power flow analysis	Power in its actual and reactive forms, frequency, voltage, current, etc.	Common monitoring	5%
		Synchro phasor	1% *
		Interconnecting DERs	1%
Electrical fault analysis (transient event states)	Differences in effectiveness between main & backup overcurrent protection systems	Primary fuse and backup relay	7.5 cycles **
		Primary and backup relays	13.6 cycles **

Here, the use of fixed equipment to pinpoint insulation faults is superior. Good layout design is essential for electrical substations in order to reduce environmental impact while providing continuous, reliable, and safe electricity. These substations are crucial parts of the power distribution network. In this post, we will go over the basics of substation layout design, including some important concepts and things to keep in mind. Industrial facility designs are based on these required clearance and distance standards. With an unwavering commitment to safety with environmental preservation as our guiding principles, precise distances are established by project specifications, local restrictions, and thorough safety evaluations. Several important factors should be considered at the Substation location to guarantee safety, reliability, and efficiency.

2 SPOS analysis

Numerous casualties in the construction business make it one of the greatest accident-prone sectors, with far-reaching consequences for workers, employers, and the community at large. A great deal of unpredictability and uncertainty permeates the outdoor setting that is typical of building development. Nowadays, there is a greater likelihood of accidents due to the simple management of building construction. The use of smart site construction in recent years has led to a considerable decrease in the accident rate at construction sites. As a result, implementing safety controls on the job site is crucial for lowering accident rates.

The following are some of the many ways in which predictive and preventative maintenance may be beneficial:

The benefits include:

- less unplanned shutdowns,
- more efficient use of personnel,
- more plant productivity,
- lower instrument management costs, and
- longer gadget life.

There is a higher risk of injury on SPOSs compared to other building sites. Many factors often need to be considered in SPOS safety control. Complex factors like as equipment, people, high-voltage transmission lines, distant locations, and early phases of inadequate power supply make management more difficult than on conventional building construction sites. This work aims to enhance safety control in power grid construction by constructing a safety control system suitable to SPOSs. Cameras for monitoring, gadgets for wireless connection, and intelligent sensors make this system possible. The control center, the environment, the equipment, and the people using them all work together in real time.

2.1 Feature of SPOS

Predictive servicing of electrical systems involves keeping devices running well by keeping tabs on their online operating status in real-time, which is achieved by regularly collecting information about the efficiency of various electrical equipment, the distribution of heat from devices, and other factors reliant on statistical data. Consequently, the computer meticulously prepares all maintenance actions using precise data. If there is a significant abnormality, it is addressed before the whole system fails. Identifying electrical equipment defects early on helps avoid major disorders from happening, which in turn decreases downtime, maintenance costs, and enhances devices' operating time. There are a lot of ways in which SPOSs vary from regular construction sites. The unique geographical location and the unique role performed are the key factors. Here are some of the SPOS's features. One may see the SPOS of a suburban region in Figure 1. Substations are often built in outlying suburban and hilly regions. The construction region has inadequate power supply and communication network coverage as a result. There could be 10kV, 35kV, 110kV, 220kV, or 500kV high-voltage transmission lines present in an SPOS. There is a higher risk of electrical mishaps on construction sites when electricity is always on.

Intelligent substation renovation and new intelligent substation construction are the two primary scenarios in which substations are built. Keeping the electricity on is an important part of intelligently transforming old substations. As a result, SPOSs encounter a more complex environment, making it harder to attain precise safety control. Equipment safety, energy and water meter monitoring, drone monitoring, electric shock prevention, staff behavior identification, and environment monitoring are all components of SPOS's safety control system. They are corresponding to the site's environmental monitoring, people monitoring, and equipment monitoring, respectively.

2.2 Equipment safety system

The construction scenes at SPOS are intricate, and there is a wide variety of construction equipment there. The current method of safety control, which relies on taking pictures of and collecting data on construction equipment using cameras, is not capable of providing complete monitoring. As a result, in order to perform thorough safety control of SPOS monitoring, this study employs a plethora of sensors. Figure 5 is a schematic depicting the SPOS gadget safety control framework. Data uploaded from all equipment monitoring systems is shown by the red dotted line in Figure 5.

There are six constituent parts that make up the overall system for controlling equipment safety. Tower cranes, elevators, unloading platforms, construction vehicles, lofty supporting molds, and deep foundation pits have all been monitored. An information transmission network, control center, and monitoring sensors make up each subsystem. Ensuring the security of the whole building site, it accomplishes the administration and control of construction scenes. In Table 2, we how each subsystem works.

Table 2: Different applications for substation monitoring

System	Function
Tower Crane Safety Monitoring System	The tower crane's activity is tracked in real-time using monitoring sensors, which also update the BIM model. The control center can supervise the tower cranes' safety in real-time.
Elevator Monitoring System	Elevator safety control using data from sensors such lift speed, load, and passenger count.
Discharge Platform Monitoring System	Indicators like tilt angle and load capacity are used for discharge platform monitoring.
Construction vehicle	Keep an eye on the whereabouts and status of construction trucks.
High support mould monitoring system	The development of the support mold's safety status monitoring was based on a great deal of monitoring indications, which allowed for the achievement of early alert of accidents.
Foundation Pit Monitoring System	Surface deformation, fissures, and other problems may be identified as they develop in real-time inside the foundation pit. The foundation pit condition monitoring is completed.

The equipment's safety control system has electric field sensors in addition to SPOS features. Near the SPOS, there are transmission lines carrying high voltage, which might cause electrocution in the event of a construction disaster. Thus, in order to implement the control system for preventing electric shock during equipment assembly, electric field sensors are used. To pinpoint the exact spot of an accident, position sensors are essential for construction equipment, which is constantly moving. An electric shock protection warning based on two dimensions—electric field size as well as geographical location—can be realized with the integration of positioning equipment into the electric field sensor. This study updates the electric field sensor design to include an acceleration sensor, allowing for more accurate localization of the moving object. This method guarantees precise positioning by achieving real-time adjustment of the electric field sensor's location. Because environmental factors like humidity and temperature may influence electric field measurements. As a result, the electric field sensor incorporates temperature and humidity measurements into its architecture. The exactitude of the electric field analysis may be assured by combining real-time temperature and humidity readings with the electric field sensor's observed values.

2.3 Equipment status characteristics

Surge arresters, capacitor banks, voltage transformers, current transformers, circuit breakers, and transformers make up the bulk of a substation's high-voltage electrical equipment. The reliable transmission and distribution of power is ensured by these devices, which perform several activities such as voltage alteration, circuit interruption or connection, measurement of high-voltage current and voltage, and protection against lightning overvoltage. Quantifying the present status of these equipment by testing as well as online monitoring is the main emphasis of substation state assessment.

In order to ascertain whether or not an item is suitable for use in the system, electrical testing procedures examine its insulation and functioning. The most common approach compares the results of the test at the moment of the equipment's delivery to those from the manufacturer-specified ranges or from earlier measurements. Equipment condition is determined by analyzing post-test departures from these reference values and consulting with experts. In order to gather equipment characteristics in real-time, online monitoring makes use of a variety of sensors. A monitoring system receives the data and either human analysts or computer programs evaluate it. Various equipment in a substation may have their online monitoring data integrated by specialist modules in the Supervisory Control and Data Acquisition system. Insulation monitoring systems, gas chromatography results, winding and oil temperatures, current and voltage readings, and data from current and voltage transformers are all part of the data collected by transformers for monitoring purposes. Position sensors record the number and status of switch operations; temperature sensors record the temperature, and current transformers record the running current as part of the data set for monitoring switchgear. The data collected by temperature sensors, humidity sensors, and specialized monitoring devices for switchgear cabinets includes both interior and exterior temperatures, relative humidity, and partial discharge. In order to evaluate the effectiveness of the lightning arrester, data is collected by a leakage current tester. Additionally, operational conduction events may be tracked by using a discharge counter to record the frequency of discharges. Using temperature sensors, capacitor monitoring mainly focuses on the capacitors' and their peripheral devices' temperatures. Partially discharged cables, as well as their sheath and interior temperatures, are among the data points collected by cable monitoring systems.

In order to transfer electricity from a source to many loads over long distances at high voltages and currents, systems for distribution and transmission are crucial. Therefore, it is critical to monitor and regulate the different parts of these structures. Coils, clamps, or instruments with transformers were used to detect just the grid voltage and current characteristics in the past for this purpose. But their cumbersome designs make them substation-only, and the fact that they come into direct touch with high-voltage cables makes installation and maintenance a pain. A number of changes are taking place inside the power grid at the moment, such as the integration of renewable energy sources, the introduction of bidirectional power flow, automation and remote control, and so on. These advancements need small, energy-efficient sensors that can detect a broad range of grid factors, including data on magnetic fields, temperatures, humidity, acoustics, and more. This will allow for predictive management of the power grid as well as real-time monitoring over large areas. Among the many parts of the electrical power grid's outage management system, sensors are now considered crucial. Sensors' capacity to monitor networks for transmission and distribution in real time aids in either preventing interruptions entirely or mitigating their effects. The electrical grid may now undergo condition-based maintenance, which, in certain instances, can be more efficient and cost-effective than the usual planned maintenance, all thanks to sensors. Due to their exclusive responsibility for acquiring raw fault data, sensors also constitute a very important input facing component for the majority of monitoring and control systems. When it comes to analyzing the nature of the instruments' working and breakdown in the transmission as well as distribution lines, it is crucial to classify and forecast various grid metrics received from the sensors. This will allow for better predictive, adaptive, along with corrective analysis. Probabilistic risk assessment and contingency assessments using sensors greatly enhance power grid asset usage.

2.4 Sensors for safety supervision

A number of critical components of the transmission and distribution networks have made use of sensors. These components include: substations, power transformers, insulators, lightning arrestors, transmission line equipment, underground cables, power transformers, circuit breakers, battery systems, and transmission while distribution line poles. In a SCADA (supervisory control and data acquisition) system, sensors are an integral component of the input facing parts of the remote terminal units with phase measuring units. The power grid relies on accurate and discrete sensors for a number of tasks, including monitoring equipment operating temperatures, measuring rated and leakage waves, and improving distribution and transmission line monitoring using acoustic sensing. Power conductors, Insulators, power transformers, breakers, and various other parts of the power system have a variety of sensors installed, including magnetic, vibrational, acoustic, fiber optic, infrared ray, and so on.

Below is a summary of some of the most important parts of the power grid's transmission and distribution systems, along with some of the most common problems that might arise with them. There has been an explanation of the various sensors and how they work to reduce these errors.

2.5 Power transformers

The most important and costly part of a substation is the power transformer. Their primary function is to reduce the high voltages of the transmission lines to levels suitable for sub-transmission and distribution. Although power transformers are durable and can last for 60 years with proper care and safety features like surge arresters, they are still prone to a number of failures and breakdowns while in use. These can range from a rise in transmission losses to the transformer's total failure, which can cause fires and other dangers and cost millions of dollars and lives. The components of power transformers wear down over time, which is a common source of damage. Damage to the transformer may also occur via insulation deterioration, oil leakage, or oil absorption by moisture. A power transformer's functionality may also be significantly compromised by lightning, seismic activity, and line surges. Several sensors have been installed on the power transformer to keep an eye on these problems.

2.6 Overhead line power conductors

Power transmission across vast distances relies on overhead line power cables, which are vulnerable to corrosion caused by extreme weather and high voltages. Both the transmission and distribution systems rely on overhead line power wires. The following are some of the reasons why this degradation occurred. As a result of air pollution, conductor deterioration is a typical side effect of galvanization. Severe mechanical stress is placed on the power conductors by vibration damage, which includes aeolian vibration, galloping, and sub conductor oscillations. Damage to the electrical wires, including sagging and breakage, may occur as a result of extreme weather events such strong winds, rain, and snow.

2.7 Overhead line insulators

Among the primary roles of overhead line insulators is to provide a highly resistant channel for leakage currents and to fortify the power conductors mechanically so that they can endure external loads. There are many different kinds of insulators, but the most common ones are pin, suspension, strain, shackle, disc, stay, and other similar types. In the event of a flashover, insulators may be punctured or deteriorated as a result of age, mechanical stress, electrical stress, or air contaminants, all of which can induce dielectric breakdown. Horizontal transmission line insulators have been the target of many sensor deployments in an effort to detect and document the aforementioned breakdowns.

2.8 Distribution system switchgears & protective devices

Circuit breakers, reclosers, relays, fuses, sectionalizers, and other protective devices safeguard the power transformers, power conductors, and distribution side equipment against fault currents and high voltages in the distribution system. The protection mechanisms are often impacted by fault currents, which may cause sympathetic tripping, shorten the effectiveness of distance relays, disrupt relay coordination, and more. Finding faulty parts of line used to be done using faulted circuit indicators. Defected segments of the line served as indicators of the fault level. A mechanical target, such as a flag or an LED, was put up to show the problem level. Nevertheless, the time it takes to clear faults is prolonged since this process is sluggish and causes a delay in the communication among protective devices like reclosers and downstream devices like fuses or other reclosers.

2.9 Transmission line towers

Transmission towers provide ground resistance, house a variety of power conversion, safeguards, and insulation devices, and ensure the continued operation of transmission line power conductors, making them an essential component of the electrical grid. Because of their size and complexity, transmission towers are vulnerable to shifting, tilting, cracking, vibrations, along with subsidence. These concerns may lead to serious complications, including as communication network and transmission line disruptions, galloping transmission lines, settlement tilt in the tower, and even tower or conductor collapse.

2.10 Underground cables

Due to the increased dependability, stability, security, and safety that subterranean cables provide to the grid as a whole, they are quickly replacing overhead lines. Subterranean cables may be used in both the transmission and distribution networks. While burying the cables lowers the outage risk, they are nevertheless susceptible to catastrophic defects caused by partial discharge, temperature increases, cable aging, wear and tear, etc. As a result, finding and fixing cable faults is a challenging and costly ordeal. Because of this, a wide range of sensors have been created and used for identifying faults and monitoring in subterranean cables.

3 Related work

Importantly, the goal of the researchers in [14] is to decrease energy consumption and increase the dependability of electrical equipment at substations. Substation safety and stability are ensured by the AC along with DC systems used in substations. At that time, the station electrical infrastructure does not have an intelligent way to track the status of different pieces of equipment, their energy efficiency, or to alert operators to anything out of the ordinary. The integration of measuring and sensing technologies, big data applications, with artificial intelligence forms the basis of that article's monitoring technology. The system uses feature matching, recognize patterns, while machine learning to extract electrical characteristic parameters from all electrical equipment in the station. It then identifies and detects the type of equipment, its electrical information, when it is operating, its status, and indicators of energy consumption. That greatly enhances the substation safety management level by allowing holographic visual awareness of the station's electrical system's load equipment.

In order to address the safety monitoring situation, the authors of [15] suggested a hybrid routing technique that takes into account the priority of services and is wirelessly self-organizing. At the outset, they have a look at the possible outcomes of data exchange between safety monitoring equipment installed at substation and transmission sites. Next, the procedures for implementing a hybrid data routing technique that takes service priority into account are detailed. Lastly, a typical wireless self-organized networks scenario is used to verify the effectiveness of the proposed architecture. The experimental findings show that the suggested routing technique fulfills the delay QoS criteria for various priority services while minimizing transmission energy usage.

An approach to monitoring diagram verification was developed by the authors of the aforementioned article [16]. That method is based on the analysis and verification of wiring diagrams. The authors further enhanced the automatic approval logic for the entire monitoring process, from the slave end to the develop end, and then put it to use in real-world engineering applications.

A cloud-based model while improved evidence theory-based risk assessment approach for substation power surveillance systems is proposed by the experimenters of [17] to address the issues of inadequate system modeling, unclear expert evaluation opinions, and failure to take the system-wide risk into account when assessing such systems. First, the substation power monitoring system's structure and security requirements are taken into account when analyzing the system's equipment, security objectives, and threats. Then, the overall risk assessment framework for the system is established. The optimal combination assignment is then implemented using the FAHP while the modified entropy weight method. The substation power monitoring system's risk level is determined after a thorough evaluation using the cloud model and better evidence theory. The monitoring system's safety management offers a fresh perspective.

With the use of early warning and monitoring, the authors of [18] ensure that substation maintenance workers and construction workers are protected while on the job. First, the article compiles employee image data and captures images of personnel using monitoring equipment like intelligent cameras to create an image sample library. Second, the upkeep and operation of detection model is built using the HOG algorithm, CNN, and image processing algorithms. The system's accuracy is enhanced by exporting personnel images to facial recognition, intelligent detection models for safety helmets, and clothing. That enables the tracking of personnel who enter and exit the substation, and the data and intelligence level of substations safety control are effectively enhanced.

In order to tackle issues including breakdowns of equipment, energy losses, and security concerns, the researchers in [19] developed a power substation monitoring and automated control system that is based on the IoT. The system gathers real-time data on voltage, current, along with temperature from different substation components via a network of sensors. After data collection is complete, it is sent to an approved control center via an intuitive Blynk IoT app. Proactive maintenance is made possible by the use of advanced analytics and algorithms, which can detect any issues and start activities immediately. Furthermore, by keeping an eye on voltage levels as well as balancing loads, the system makes the most of available resources. Better accessibility and faster reactions to critical events are made possible by integration with the Blynk app, which allows for remote monitoring, real-time notifications, and remote-control capabilities. The results demonstrate that the suggested method enhances the substation's efficiency, reduces downtime, and boosts grid dependability, leading to a more sustainable and robust electricity infrastructure.

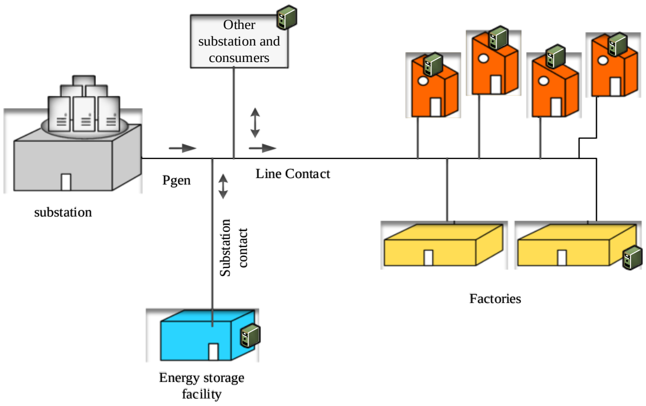

Figure1: Substation monitoring

By integrating IoT sensor networks with fuzzy logic, a Fuzzy Inference-Based Safety Monitoring Framework may provide a sophisticated and astute method of risk evaluation for substation power operations. With the complicated electrical environment comes inherent uncertainties, and this system goes beyond basic alarm triggers to address them.

3.1 Role of IoT sensor networks

By collecting detailed information in real-time from key locations within the substation, the Internet of Things sensor network lays the groundwork for the framework. In order to keep tabs on things like transformers, circuit breakers, and busbar temperatures, these networks may use a variety of sensors.

- Equipment vibration detectors for early mechanical failure detection
- Acoustic sensors to detect any abnormal noises that might be signs of a developing problem
- Humidity, gas (such as SF6 gas leaks), and air quality sensors for use in environmental settings
- Electrical devices that can measure power, current, and voltage

The substation's operational health is comprehensively monitored in real-time by continually collecting and wirelessly transmitting this data to a central processing unit or a cloud platform. An IoT sensor network gathers real-time data, and fuzzy logic offers a sophisticated, intelligent method of risk assessment in a Fuzzy Inference-Based Safety Monitoring Framework for substation power operations. Rather than a static file, this framework's dataset is a real-time feed from a number of sensors.

a. Dataset from IoT Sensor Networks

A time-series compilation of data points from different sensors placed throughout the substation constitutes the dataset for this architecture. It is an ever-evolving dataset that is alive and well. This dataset contains important variables such as:

- Electrical Parameters: Power (kW), Frequency (Hz), Current (A), and Voltage (V). These are the most basic signs of the stability and load on the substation.
- Thermal Parameters: The temperature, in degrees Celsius, of essential parts including busbars, circuit breakers, and transformers. When anything starts to overheat, it's usually a sign that something is wrong.
- Environmental Factors: Humidity, temperature, and gas levels (such as SF6 in the event of a

4 Proposed work

4.1 Research idea

One common method of substation management today is the intelligent simulation system. In order to determine how to maximize the substation intelligent simulation system's safety using an improved genetic algorithm, this research investigates the safety operation analysis of such a system. This article found that data from substation intelligent simulation platforms based on improved genetic computations is better than data from traditional substation intelligent simulation systems. This proves that improved genetic techniques may enhance the security of substation intelligent simulations systems. The testing involved comparing the number of vulnerabilities discovered while the number of illegal intrusions in the two systems, which is given in fig 1.

leak). Both the functionality and security of electrical appliances might be compromised by these.

4.2 Data preprocessing

The dataset represents a power transformer's simulated operational data set spanning a decade, including both typical and out-of-the-ordinary working scenarios. Time stamps and anomaly labels are attached to each record. In brief, the following are some of the many electrical, thermal, chemical, along with frequency response characteristics captured by the measured variables:

- Currents and voltages, both primary and secondary, as measured electrically ($V_{prim\ mms}$, $V_{suc.ms}$, $I_{prim.ms}$, $I_{sec.ms}$).
- Oil temperature and room temperature are the thermal parameters (T_{cal} , T_{eav}).
- Hydrogen concentrations in oil-dissolved gases (H_2), methane (CH_4), acetylene (C_2H_2), besides carbon monoxide (CO), stated in ppm.
- FRA (frequency response analysis): tangent delta, capacitance, and impedance magnitude and phase ($C_p, |z|, \angle Z, TgD$) assessed using four different bands of frequencies ($100\ Hz - 1kHz, 1kHz - 10kHz, 10kHz - 100kHz, 100kHz - 1\ MHz$).
- FRA in action (FRACTIVE): identical set of FRA characteristics assessed independently on stages A, B, and C.

The dataset has about 60 descriptive characteristics in total, in addition to the columns for timestamps and anomalies. By excluding the timestamp and anomaly, we were able to generate the feature matrix X. To guarantee that each feature had a zero mean with unit variance, we used Z-score normalization:

$$z_i = \frac{x_i - \mu}{\sigma} \quad (1)$$

where x_i σ is the standard deviation, μ represents the mean, and is a feature value.

4.3 Dimensionality reduction

Principal Component Analysis (PCA) was used to reduce computational cost and duplication among strongly connected data. A minimum of 20% of the overall variance was maintained by selecting a number of retained parts k such that:

$$\sum_{i=1}^{k} \lambda_i \geq 0.20 \quad (2)$$

- Mechanical Parameters: Data on vibration and sound to identify mechanical wear and arcing in its early stages

where λ_i stands for the covariance matrix's i-th eigenvalue. Finding a happy medium between computing efficiency and model correctness led to the selection of this criterion. Processing the whole set of features would greatly raise training cost because to the high number of monitored variables. Thus, in order to expedite learning while preserving representative data, this research used an arbitrary variance retention of 20%. You should know that this decision is case-specific; other uses could call for a different retention percentage. The resultant matrix of reduced features $X_{PCA} \in R^{n\times k}$ before being categorized.

By obtaining the mean of each row in the training sample matrix and subtracting it from each feature value in that row, we can create an additional two-dimensional feature matrix, which standardizes the overall sample matrix. The testing method also requires a standardization procedure for the test sample's feature vectors,

$$x_{v^*} = x_{v_i} - \overline{x_{iq}} \quad (3)$$

where $\overline{x_{ij}} = \frac{1}{n}\sum_{i=1}^{n} x_{ij}$. We compute the covariance matrix of the training sample's new feature matrix. The covariance matrix's eigenvalues and eigenvectors are computed, with the eigenvalues ordered from most to least significant. In the findings and discussion portion of this study, we will compute and analyze the eigenvalue contribution. Dimension reduction as well as performance comparison may be facilitated by obtaining alternative projection matrices of the ideal projection axis, which are created by choosing different eigenvector sequence lengths in a large-to-small order.

The projection matrix is used to project the features of each 1 s data set (training sample, test sample) after standardization. The result is a new set of features for both the training and testing samples, which can be adjusted to achieve different dimensional reduction effects by choosing different eigenvector sequence lengths.

When the electrical grid is running smoothly or has a three-phase fault, the asymmetrical fault initiating requirement is not fulfilled since the zero-sequence and negative-sequence currents are almost nonexistent. Here, we use the blocking criteria of low-order harmonic excitation current and use the current magnitude ratio criterion to get the conclusion. The outcome of an asymmetrical grid fault is dictated by both the current magnitude criteria with the low-order harmonic excitation current requirement in tandem. One must first measure the transient current at the grounding point of the N line in order to determine the amplitude of the lower-order harmonic elements. The ground fault among the two neutral locations is then detected after identifying the low-order harmonic current excitation criteria.

4.4 Fuzzy reasoning model

Regular inspections via operation and maintenance staff are necessary because the substation environment effects interior equipment. Aside from automated monitoring, these inspections cover topics like checking the temperature at contact while wire connection points, checking the integrity of aluminum stranded wire, evaluating the interference caused by plants or animals, checking the oil level in oil-filled devices, and monitoring the gas pressure of SF6 equipment.

- Noise pollution, electromagnetic field exposure, and aesthetics are all important environmental factors that must be considered while designing a substation. Substations may be designed and landscaped to fit in with their surroundings.

The decision-making layer takes fire likelihood into account while making judgments, along with other criteria. There can be no way to tell whether a fire is happening when the probability is precisely 0.5. In order to enhance the degree of decision-making, the length of the fire signal is included as a decision-making component, and fuzzy theory is then applied. There are four tiers to the decision-making level's output: no fire, warning, alarm, and severe alarm. First, the input and output signals are fuzzified in the fuzzy reasoning phase. Then, the fuzzy rules are established. Interim relationship between fuzzy sets is defined by equation (4). For a fuzzy implication relationship R, rule i is the corresponding rule. The last step is to create the input/output rules table.

$$R_i = (Y_1(i) \text{ and } Y_2(i) \text{ and } \mathrm{T}_i)$$
$$R(x, y, z, u) = U_{i=1}^{n} R_i \qquad (4)$$

The developed fuzzy inference system's output surface is shown in Table 2 and Table 3.

Fuzzy rules example

1. IF **Temperature** is High AND **Humidity** is Wet THEN **Safety Index** is Danger
2. IF **Voltage** is Stable AND **Gas Level** is Safe THEN **Safety Index** is Safe
3. IF **Personnel** is Present AND **Gas Level** is Warning THEN **Safety Index** is Caution

Table 2: Fuzzy input variables

Variable	**Range**	**Membership Functions**
Temperature	0–100°C	Low, Normal, High
Voltage	0–500V	Stable, Fluctuating, Overload
Gas Level	0–100 ppm	Safe, Warning, Critical
Personnel Presence	0–1 (binary or probability)	None, Present
Humidity	0–100%	Dry, Moderate, Wet

Table 3: Output variable

Output	**Range**	**Categories**
Safety Index	0–100	Safe, Caution, Danger

Membership function

At its core, the concept of a fuzzy set includes the membership function (x). It finds out how much of a fuzzy set member a certain element is. Depending on the problem's context, the choice of a suitable function for membership is often subjective. The singleton, triangle, trapezoidal, and Gaussian shapes among the most popular choices for functions related to membership. The suggested method defines the input and output variables' membership functions using a trapezoidal membership function. Energy consumption $(E\mathbf{O})$ is the only output of this system. Despite the convenience of the triangle membership structure, the research's key parameters—which include temperature, set-points, price, and humidity—are best described using the trapezoidal membership function because these variables do not exhibit abrupt changes in value and tend to stay constant over extended periods of time. Therefore, the simplicity of these flattened line membership processes is a benefit.

Algorithm for Fuzzy Logic
Step 1: Providing the scope of membership functions and setting the input and output variables. **Step 2**: Input value is outputted with an alternate membership degree [0, 1] once the membership functions are defined as the fuzzy processing software. **Step 3**:

We are creating a fuzzy rules foundation. The semantic transform of "IF X1 is A AND X2 is B, THEN Y is C" is used by designers to build a fuzzy rule base which will serve as the basis of the fuzzy inference engine. This base is based on experience or knowledge from experts.

Step 4:

Using an interactive fuzzy operation management rule basis, the outcomes are produced by fuzzyification inference

Step 5:

Defuzzification: It used a membership of degrees to aggregate the results and get an output value.

The process of establishing rules in a system becomes more tedious as the number of rules needs to be established grows. A lot of methods have been developed to make rule definition easier. This research proposes a mechanism based on combinatorics and weightage for the automated development of rule bases. As seen in Algorithm 1, $Score$ is computed by assigning a weightage to each membership associated with a single input parameter. This weightage is then utilized to assign values to the resultant variables. The following are the main FLC procedures: The initialization and definition of all member functions of the system characteristics takes place during the fuzzification process, which is the first phase. Step two involves selecting an appropriate output fuzzy value and establishing the rules in the rule base by adding weights to the membership functions of the input parameters. Step three involves assessing energy use with the help of the Mamdani FIS and the Sugeno FIS. To achieve a clear number for the energy usage, defuzzification is done after the rule assessment. The last step is to compute the remaining performance metrics.

After the membership functions of the input parameters are weighted in the second stage, we add a parameter $Scofe$ to indicate energy consumption and avoid the combinatorial expansion of IF-THEN rules. When $Scoae$ is low, energy usage is also low. To get the $Tcofe$, we add up the weights given to the variables' membership functions. Low, medium, and high membership functions are represented by 0, 1, and 2 weights, respectively, in the weight system.

Occupancy constitutes the only exception; it indicates if there are any tenants in the building and has a binary value of 0 or 1. When $Tcofe$ is computed by summing the weightings of membership functions for the the parameters being input, the approach utilized for automated rule generation uses a combination of these parameters, where order is irrelevant, and they adhere to the commutative property. Here is the $Scofe$ at any given time:

$$Score = \sum_{i=1}^{16} W(vi) \qquad (5)$$

where W is weight and vi are the variables.

4.5 Substation failure control strategy

The failure alarm host communicates with the failure suppression system to implement appropriate failure suppression procedures according to the decision-making evaluation of the estimated sample failure probability value. The substation runs smoothly when there's no failure; when there's a warning, the failure extinguishing gadget isn't turned on, but the substation staff keeps an eye out for unusual signals and goes to the warning location if needed; when there's an alarm, the failure alarm host gets the signal to turn on the apparatus immediately; and when there's a serious alarm, the apparatus is turned on immediately, the power is turned off, and the substation staff responds to the accident. The failure alarm host communicates with the failure suppression system to implement appropriate failure suppression procedures according to the decision-making evaluation of the estimated sample failure probability value. The substation runs smoothly when there's no failure; when there's a warning, the failure extinguishing gadget isn't turned on, but the substation staff keeps an eye out for unusual signals and goes to the warning location if needed; when there's an alarm, the failure alarm host gets the signal to turn on the apparatus immediately; and when there's a serious alarm, the apparatus is turned on immediately, the power is turned off, and the substation staff responds to the accident.

4.6 Input signal correlates with an output signal

In the text, the input signal is set to where i=1, 2,…,n. The output signal is set to j=1, 2…, m. This is the connection between them:

$$\begin{gathered} S_k = \sum_{i=1}^{\pi} v_{ki} X_i + v_{k0,} 1 \le k \le h \\ Z_k = \sigma(S_k), 1 \le k \le h \\ Y_i = \sum_{k=1}^{n} \omega_k Z_k + \omega_{p,1} \le j \le m \end{gathered} \qquad (6)$$

The hidden layer input is S_k, the hidden layer output is Z_k, v_k the weight of the connection between the input and hidden layers, the threshold of the hidden layer, the weight of the connection between the hidden and output layers, and the output layer threshold are all represented by v_{ki} and ϋ_0, respectively.

To determine the error, we simulate the output of the training samples. Then, we update the weights and thresholds to match the error criteria by propagating the error backwards. With the error function:

$$E = \frac{1}{2}\sum_{k=1}^{t} \sum_{k=1}^{m} \left(q_k^l - p_k^d\right)^2 \quad (7)$$

5 Results & discussion

5.1 Implementation

We measured the root-mean-square current dimensions for the breaker in the protective relays and modeled the electrical fault currents in MATLAB/Simulink.

(i). Assessment indicators

The paper uses two error indices—the root means square error (RMSE) and the mean absolute percentage error (yMAPE)—to assess the accuracy of the substation failure warning model. The MAPE and RMSE metrics assess the model's precision. The MAPE equation is in () while the RMSE equation is in (8).

$$y_{\text{MAPE}} = \frac{1}{n}\sum_{i=1}^{n} \left|\frac{y_a(i) - y_p(i)}{y_a(i)}\right| \quad (8)$$

$$y_{\text{RMSK}} = \sqrt{\frac{\sum_{i=1}^{n} \left[y_a(i) - y_p(i)\right]^2}{n}} \quad (9)$$

$y_s(i)$ and $y_p(i)$ are the current and projected probabilities of failure.

5.2 Accuracy of measured current and voltage

The % errors for both voltage and current measured on the RTS and HMI were computed applying the measured phases currents and voltages for the power meters and protection relays. Equation (10) was used to determine the percentage inaccuracy of the observed currents ($E_{\%}$ in) in phase A, B, or C.

$$E_{\%}\,/\text{In} = \frac{I_{nWMI} - I_n\,\text{FTS}}{I_n\,\text{KTS}} \times 100 \quad (10)$$

where $I_n RTS$ which is the n(" "A," "B," or "C") phase current measured in amperes from the RTS, and I_n HMI which is the n(" "A," "B," or "C) phase current measured in amperes from the HMI of the IEDs.

We used Equation (9). to get the percentage error for the observed n(" "A," " B, or C) the phase voltages ($E_{\%}$ 〖" " V_n) in which V_n RTS is the $n(A, B$, or $C)$ phase voltage collected from the RTS in volts, and $V_n n_{HM}$ is the $n(A, B$, or C) phase voltage collected from the IEDs' HMI in volts.

Table 4: The system monitored variables.

Parameter	Busbars	Generators	Dynamic Loads	ML Model
Frequency		X	X	√
Rotor Angle		X		√
Angular Speed		X		√
Torque		X		√
Voltage	X	X	X	√
Power Factor	X	X	X	√
Apparent Power	X	X	X	√
Active Power	X	X	X	√
Current	X	X	X	√
Reactive Power	X	X	X	√

This study two options when using a generator: lock mode and free mode. When locked into lock mode, the generators produce electricity in direct proportion to the speed of rotation of the primary mover. When operating in free method, the generator responds to mechanical torque. The sound frequency in the generators may be measured by observing its angular velocity, which varies with its load, which is given in Table 5.

Table 5: Simulation parameter

Parameter	Values
Conductor radius r_c (mm)	14.68
Insulation radius r_{in} (mm)	18.22
Sheath radius r_s (mm)	20.96
Line length L (m)	600
Effective resistance R_e (Ω/km)	0.56
Distributed capacitance C_d (μF/km)	0.529
Ground resistor R_G (Ω)	5
Supply voltage U (V)	390 (RMS)
Frequency f (Hz)	60

5.3 Comparison and analysis of effectiveness

We utilized data from a variety of sources linked to the primary transformer, including online surveillance, testing, maintenance, and operation, and environmental conditions, to evaluate the performance of the suggested approach for assessing the quality of electrical equipment with previous classifier algorithms. After that, we used 70% of the dataset for training and 30% for testing purposes, using the steps outlined in (1), to evaluate the electrical equipment's quality. Then, we used a number of performance measures to forecast the primary transformer outcomes, including accuracy, recall, precision, F1-score, the (ROC curve, as well as AUC, and we compared our method's efficacy with other classifier algorithms, which is given in Table 6.

Table 6: Performance metrics for each method

Classifiers	State	Accuracy	Precision	Recall	F1-Score
This method	Normal	92.06%	87.04%	93.28%	85.16%
	Suspicious	95.20%	87.30%	87.70%	86.70%
	Abnormal	98.22%	97.18%	93.44%	94.79%
FAHP	Normal	94.11%	86.94%	91.37%	87.12%
	Suspicious	90.23%	89.14%	83.72%	83.96%
	Abnormal	97.13%	99.14%	94.70%	99.71%
HOG	Normal	92.45%	93.33%	83.11%	86.59%
	Suspicious	90.83%	81.78%	89.86%	86.91%
	Abnormal	99.86%	93.73%	93.78%	95.60%

In both the normal and attention phases, the suggested technique shows better categorization performance. Its accuracy and recall for aberrant states are better than the HOG and FAHP models, but its performance is somewhat worse overall. Increases in AUC and improvements to the ROC curves demonstrating decreased FPR and increased TPR are indicators of the method's better performance. The dependability of electrical equipment may be evaluated and choices about shutdown, examination, or maintenance needs can be informed by this performance.

6 Conclusion

When it comes to addressing operational dangers at substation power plants, the Fuzzy Inference-Based Safety Monitoring Framework leveraging IoT sensor networks provides a robust, interpretable, and powerful solution. This framework improves productivity and safety in complicated, ever-changing situations by integrating fuzzy logic's reasoning capabilities with the IoT sensors' real-time awareness. Problems arise due to the multi-factor influence and complexity of data pertaining to electrical equipment status monitoring. Computing association rules becomes more complicated as datasets expand due to the exponential growth in the total amount of candidate itemset. Addressing these highlighted problems will be the focus of future research as we refine the framework for applications in various and complicated situations. Finally, this technique shows a lot of promise and is useful for assessing the condition of substations' high-voltage electrical equipment.

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