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PREDICTIVE ANALYSIS OF STREET LIGHT OPERATIONS: EXPLORING ENVIRONMENTAL FACTORS AND FAULT DETECTION IN URBAN LIGHTING INFRASTRUCTURE

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ABSTRACT
Street lighting is essential for urban safety and security during nighttime, but traditional maintenance methods are often reactive and inefficient. Typically, maintenance relies on scheduled inspections and manual fixes, leading to delays in addressing faults, higher operational costs, and increased safety risks due to unexpected outages. These challenges highlight the need for a proactive, data-driven approach to managing street light operations. Predictive analytics, powered by data collected through sensors and IoT devices, offers a promising solution. By continuously monitoring street lights and analyzing environmental factors, predictive models can anticipate potential failures before they occur. This approach optimizes maintenance schedules, reduces energy consumption, and prevents service disruptions, resulting in significant cost savings and improved reliability. The absence of such predictive systems causes inefficient use of resources, greater energy waste, safety hazards, and operational interruptions. Integrating machine learning algorithms into street light management enables fault detection and diagnosis in real-time, supporting faster and more accurate decision-making. The proposed system focuses on building a comprehensive predictive analysis framework that includes data acquisition, processing, machine learning-based prediction, fault diagnosis, and decision support. Continuous evaluation ensures system accuracy and adaptability. Implementing this predictive maintenance system can transform urban lighting infrastructure by enhancing operational efficiency, reducing maintenance costs, and promoting sustainability. Ultimately, it improves public safety and the quality of urban life by ensuring well-maintained, energy-efficient street lighting, contributing to safer and more vibrant cities.

1.INTRODUCTION

The history of street lighting traces back to ancient civilizations, where cities illuminated streets using oil lamps or candles to improve safety and navigation after dark. [1] The first widespread use of gas lamps for street lighting emerged in the early 19th century, revolutionizing urban landscapes and fostering economic growth. However, gas lighting had limitations, including high maintenance costs and safety hazards.

[2] The advent of electric street lighting in the late 19th century marked a significant milestone in urban development. [3] Thomas Edison's invention of the incandescent light bulb paved the way for

widespread electrification, transforming cities worldwide. [4] Electric street lights offered numerous advantages over gas lamps, including lower maintenance costs, longer lifespan, and improved illumination.

[5] Throughout the 20th century, advancements in lighting technology, such as fluorescent and LED bulbs, further enhanced street lighting efficiency and performance. [6] The integration of automation and remote monitoring systems in the late 20th and early 21st centuries ushered in a new era of smart street lighting, enabling proactive maintenance and energy optimization.

[7] Today, street lighting continues to evolve with the emergence of smart cities and IoT-enabled infrastructure. Modern street light systems leverage data analytics, machine learning, and sensor technology to optimize energy consumption, enhance safety, and improve overall urban quality of life.

2.LITERATURE SURVEY

The study in [11] presents a remote management system for streetlights based on WSN and dimmable ballast with digital addressable lighting interface (DALI) interface. Digi XBee-Pro® 868 Radio Frequency with an Arduino microcontroller is employed to realise a single-level wireless communication network for the smart streetlights. The implemented results show that leveraging WSN with DALI ballast offers a half-duplex communication which can transmit a large number of parameters regarding smart streetlights. Nevertheless, WSN-based communication network is an ideal candidate for materialising data transmission in smart streetlight deployments. Single-level WSN-based smart streetlight systems are presented in [12,13]. To fully realise the WSN network, JN5148 [13], and JN5139 [12] wireless transceivers, which are based on JenNet protocol are utilised for hardware implementation in their smart streetlight systems. From scalability purposes, the systems can be extended for up to 2000 streetlights, which meet the smart streetlight requirements. In a similar way, WSN-based smart streetlight systems are discussed in [14,15], where [14] mainly focuses on developing a new efficient routing network algorithm to meet specified requirements for streetlight applications. Yusoff *et al*. [15] present preliminary studies on the development of a practical WSN-based smart streetlight system.

The study in [16] introduces a preliminary design and a simulation for a smart highway lighting management system based on road occupancy. The proposed system utilises WSN for detecting the presence of vehicles along the road. According to the obtained information via WSN regarding the occupancy of the road, the system applies proper control actions to streetlights. Mendalka *et al*. [17] provide a short study on WSN-based intelligent streetlights. This study reports that integrating WSN to the streetlights not only provides a platform for new additional services directly related to the streetlights but also sets the stage for telemetry and intelligent transportation applications.

The study in [18] proposes a traffic-aware streetlight for smart cities using WSN-based autonomous sensors. In the proposed system, each streetlight pole incorporates a wireless sensor node with a short-range wireless communication module in order to detect road users and share the information with nearby streetlight poles. Nevertheless, utilising the WSN-based autonomous sensors, the proposed system detects the presence of vehicles and pedestrians, and accordingly controls the illumination of streetlights. In [19], a WSN-based dimmable streetlight system is presented. The system is utilised Low-power Wireless Personal Area Networks for implementation due to its effective routing protocol and the ease of scalability for smart streetlight applications.

The study in [8] reports the prototype of a smart city initiative in Budapest in which various WSN-based sensors are installed on public lighting to measure the environmental-related data. The proposed system takes advantage of 700 WSN-based sensors at 70 locations to monitor environmental data in District XII of Budapest, Hungary. From a topology perspective, the implemented WSN-based system reaps the benefits of a star topology to directly connect the system to a data centre. In [20], an intelligent energy-positive streetlight system is investigated. The proposed system provides adaptive, energy-efficient lighting service via the wireless communication network. In this system, the streetlight poles are connected to inform their neighbours regarding the detected traffic scenarios.

ZigBee, which is defined by ZigBee Alliance, is considered as a low-power wireless communication network based on IEEE 802.15.4. This communication network stresses on some characteristics, such as low cost, high reliability, self-healing, and low power. One of the applications of ZigBee standard is lighting control. Leveraging ZigBee communication network, authors in [21,22] propose energy-efficient light-emitting diode (LED)-based smart streetlight systems. The proposed system in [21] consists of ZigBee-based mesh networked streetlights, gateway node, and management software with the objective of real-time monitoring and control of the lighting system. Intelligent systems based on ZigBee wireless network are proposed in [23,24] for streetlight control and measurement applications. The proposed systems mainly aim at adding communication network via the integration of IEEE 802.15.4 ZigBee compatible transceivers to the streetlight poles for turning high pressure sodium (HPS) light on/off.

In [25], a remote-control system based on ZigBee wireless network is proposed to efficiently manage streetlights. The proposed system utilises a combination of sensors to control and guarantee the desired system parameters, where the streetlights' information is transmitted to a control terminal by using ZigBee transceivers. The ZigBee wireless communication provides the intelligent streetlights to be efficiently planned and maintained from a central station. Leveraging ZigBee communication network, the study in [26] proposes power quality measurements embedded in smart streetlights. The proposed system is designed to control and manage the streetlights parameters, measure several power quality indicators, and provide a single-level communication network for information exchange with a supervisory system. Single-level ZigBee interface is employed for the sake of communication between the smart streetlights and the software supervisor, owing to its low power consumption, low cost, and ease of scalability. In terms of physical topology, the ZigBee communication offers mesh networking for data transfer over long distances.

Wireless communication of LED streetlights based on 2.4 GHz ZigBee protocol is studied in [27]. The experimental results demonstrate that the 2.4 GHz ZigBee network meets the data transfer requirement for implementing the LED streetlights. The study in [28] proposes a streetlight monitoring and control system based on a single-level ZigBee wireless network. This study only introduces the ZigBee-based streetlight system with the objective of reducing the cost associated with maintenance and energy consumption. Authors in [29] also present a ZigBee-based streetlight system with the goal of reducing maintenance time and cost associated with lighting operation. This study claims that after investigating various communication network characteristics for integrating with streetlight system, ZigBee communication network is selected for transferring data between concentrator and remote streetlight control terminals.

The study in [30] focuses on the design and realisation of general packet radio services (GPRS)-based communication technology for smart streetlights. In order to ensure the security of the GPRS communication network, a cyclic redundancy check coding is utilised. The proposed GPRS communication technology is applied to smart streetlights, where the implemented experimental results justify the performance of GPRS wireless communication network for smart streetlights applications.

The study in [31] proposes a smart streetlight system by leveraging a wireless technology network called vehicular *ad-hoc* networks (VANET). VANET includes vehicle-to-vehicle and V2I communications via wireless technology. VANET is utilised in the proposed system to determine the presence of vehicles and also measure vehicles' speeds in real-time. The main advantage of integrating VANET in smart streetlights is that it lowers the cost of system deployment, as VANET infrastructure is already available. Leveraging wireless global system for mobile communication

(GSM) network, a smart streetlight system is proposed in [32] that aims at turning the streetlights on and off by sending short message service via the GSM network.

3.PROPOSED METHODOLOGY

This research focuses on developing a predictive analysis framework for street light operations by first importing and preprocessing the data, converting categorical variables into numbers, and extracting time-related features. It includes exploring the data for missing values and visualizing patterns using charts to understand fault types and environmental factors.

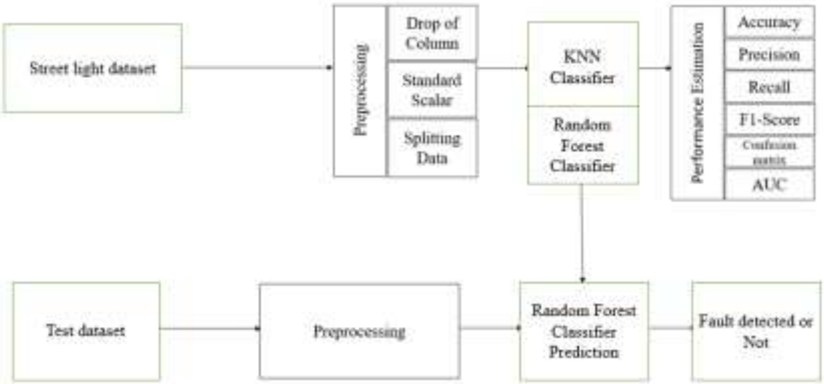

Fig. 1: Block diagram of proposed system architecture.

To handle any imbalance in fault data, techniques like SMOTE are applied to create a balanced dataset. The data is then split into training and testing sets, and machine learning models such as K-Nearest Neighbors and Random Forest are built to predict faults. Finally, the models are evaluated using metrics like accuracy, precision, recall, and F1-score, along with confusion matrices and classification reports, to ensure they accurately identify street light faults.

3.1 Random Forest Classifier

Random Forest is a popular machine learning algorithm that belongs to the supervised learning technique. It can be used for both Classification and Regression problems in ML. It is based on the concept of ensemble learning, which is a process of combining multiple classifiers to solve a complex problem and to improve the performance of the model. As the name suggests, "Random Forest is a classifier that contains a number of decision trees on various subsets of the given dataset and takes the average to improve the predictive accuracy of that dataset." Instead of relying on one decision tree, the random forest takes the prediction from each tree and based on the majority votes of predictions, and it predicts the final output. The greater number of trees in the forest leads to higher accuracy and prevents the problem of overfitting.

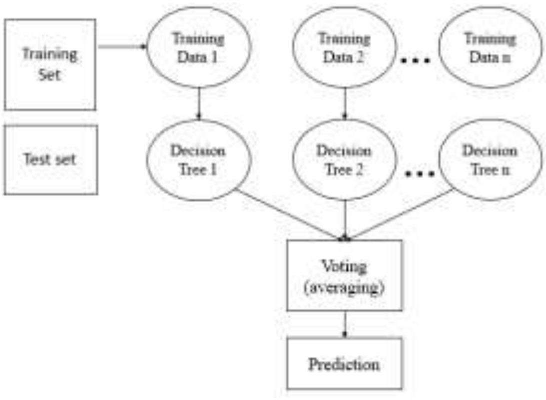

Fig. 2: Working flow of Random Forest Classifier.

Step 1: In Random Forest n number of random records are taken from the data set having k number of records.

Step 2: Individual decision trees are constructed for each sample.

Step 3: Each decision tree will generate an output.

Step 4: Final output is considered based on Majority Voting or Averaging for Classification and regression respectively.

4.RESULTS AND DISCUSSION

The dataset used in this research contains various features that provide detailed information about street light operations. The bulb_number serves as a unique identifier for each individual street light bulb, allowing specific units to be tracked. The timestamp records the exact date and time when each data observation was made, offering important temporal context for analyzing street light behavior over time.

Several electrical parameters are included to monitor the functioning of the street lights. Power_consumption measures the electrical power used by the bulb in watts, reflecting its energy usage. Voltage_levels indicates the voltage supplied to the bulb in volts, while current_fluctuations capture variations in the electric current passing through the bulb, measured in amperes. Additionally, current_fluctuations_env represents the changes in electrical current in the surrounding environment, providing insight into external electrical disturbances near the street light.

Environmental data also plays a key role in the dataset. The temperature feature records the ambient temperature around the street light in degrees Celsius, which can affect the bulb's performance. The environmental_conditions attribute describes the weather and atmospheric conditions at the street light's location, such as clear skies, rain, or fog, as well as factors like humidity or pollutants.

Finally, the fault_type feature categorizes any faults or malfunctions detected in the street light, such as no fault, short circuits, voltage surges, bulb failures, or flickering lights. This helps in diagnosing issues and understanding the operational status and health of each street light unit.

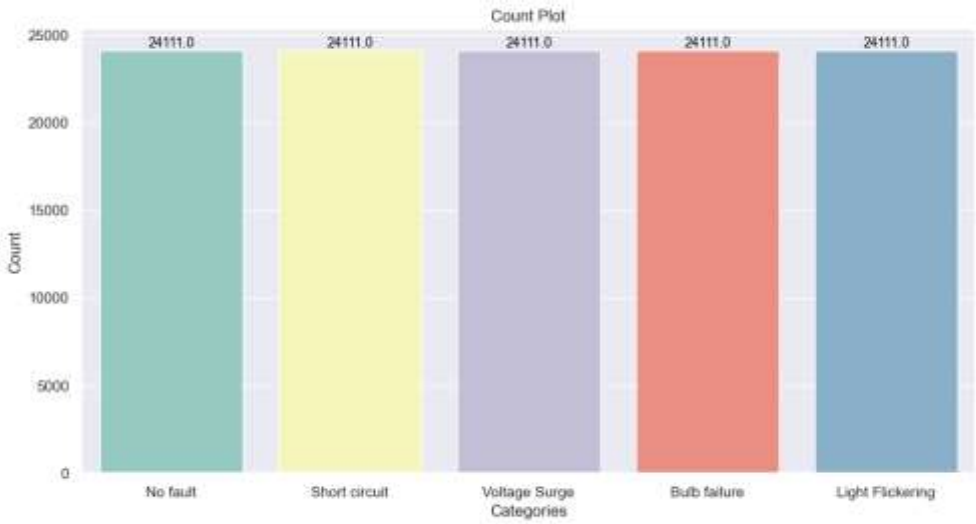

Fig. 3: Presents the count plot of Street light Fault dataset.

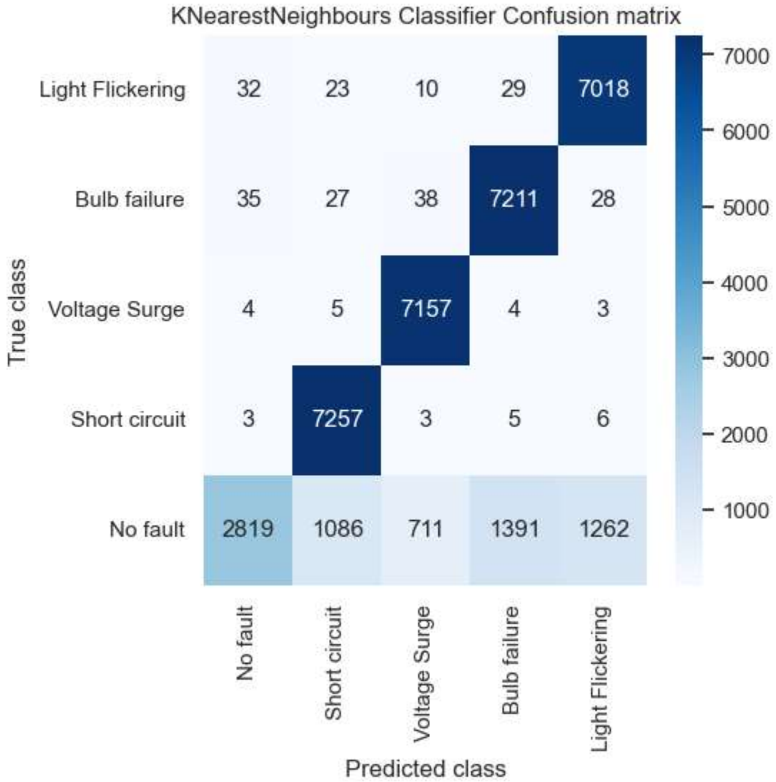

Fig. 4: Confusion matrix of KNN Classifier model.

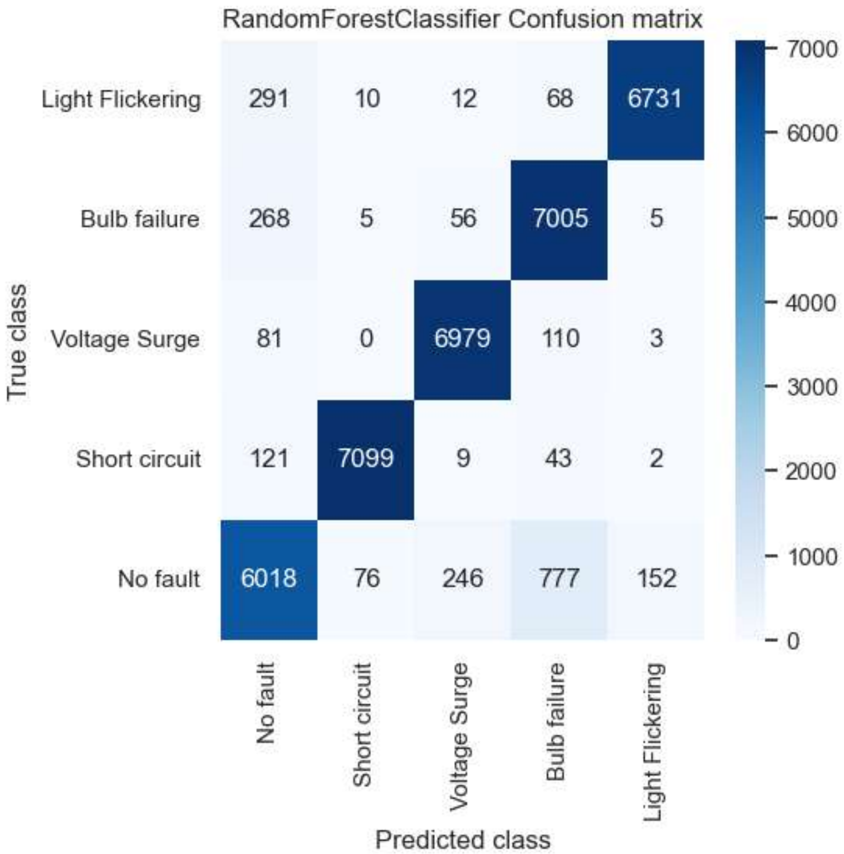

Fig. 5: Confusion matrix of Random Forest Classifier model.

Fig. 4 confusion matrix of the KNN Classifier model visually represents the performance of the model in classifying different categories of mouth diseases. It provides a clear overview of the true positive, true negative, false positive, and false negative predictions made by the model for each class.
Fig. 5 confusion matrix of the Random Forest Classifier model illustrates the model's performance but specifically for this classifier. It provides a visual representation of how well the model predicts the actual classes of Fitness activities, aiding in understanding its activities.

	Algorithm Name	Precison	Recall	FScore	Accuracy
0	KNearestNeighbours Classifier	88.415028	87.051708	84.832938	86.990903
1	Random Forest Classifier	93.652906	93.554269	93.541543	93.543838

Fig. 6: Performance comparison of algorithms.

Fig. 6 comparison table of performance metrics presents a comprehensive overview of the performance of different classifiers, such as KNN Classifier and Random Forest Classifier. It allows for a direct comparison of metrics such as accuracy, precision, recall, and F1-score

5.CONCLUSION

The development of advanced stator fault detection strategies for PMSMs is essential for ensuring reliable and uninterrupted operation in industrial applications. By leveraging cutting-edge technologies such as machine learning and sensor fusion, researchers aim to overcome the limitations of traditional maintenance methods and develop proactive fault detection systems capable of accurately identifying stator faults in real-time.

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