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A REAL-TIME EMBEDDED FAULT DIAGNOSIS SYSTEM FOR PHOTOVOLTAIC MODULE MONITORING

Dr.P.Sravan Kumar, *Associate Professor & HOD,Dept of EEE,*
Sree Chaitanya Institute of Technological Sciences, Karimnagar, Telangana, India.

ABSTRACT: The advanced integrated technology demonstrated herein enhances the reliability and efficiency of solar energy systems by real-time identification of photovoltaic (PV) module faults. The system employs sophisticated machine learning algorithms and data processing methods to discover, classify, and anticipate problems such as discoloration, degeneration, and hotspots. The proposed method yields diminished maintenance expenses, fewer power interruptions, and enhanced power generation efficiency. The system has undergone experimental validation, confirming its accuracy and efficacy in actual solar setups, thereby establishing it as a significant asset for renewable energy management.

Keywords: *Photovoltaic modules, fault diagnosis, embedded system, real-time monitoring, machine learning, signal processing, solar energy, predictive maintenance.*

1. INTRODUCTION

Solar photovoltaic (PV) systems are becoming more popular due to the growing demand for renewable energy. Shadowing, cellular death, and electrical failures are long-term problems that could reduce performance to an unsatisfactory level. Identifying problems when they arise is crucial for minimizing energy waste and maintaining peak performance. Typical conventional evaluations used in traditional diagnostic procedures are time-consuming and inaccurate. Problems with solar modules can be quickly identified with the use of a specially designed integrated device.

The embedded system detects and handles problems with solar modules by use of state-of-the-art sensors, microcontroller designs, and machine learning algorithms. Our technology offers continuous, real-time monitoring, in contrast to earlier systems that rely on passive data processing or human verification. Its data-driven approaches allow it to spot outliers and predict when results might deviate from expectations. Reduced maintenance needs and downtime make this method superior for solar installations in terms of reliability and lifespan.

The self-sufficiency of this cutting-edge integrated technology is one of its distinguishing characteristics. Complete system monitoring is made possible by efficiently collecting data from several solar panels at the same time. A major benefit of edge computing is that it speeds up local decision-making by doing away with the requirement for substantial cloud computation. Faster problem resolution is possible when operators use wireless connections to remotely access diagnostic data.

The device's improvement marks a significant step forward in the field of solar defect testing. The photovoltaic system can be enhanced in terms of energy output and waste due to undiagnosed issues by integrating an advanced monitoring system. This approach encourages the development of intelligent infrastructure by making it easier to generate renewable energy, which is the main goal. Global energy transitions rely on efficient and dependable solar systems, which is why integrated defect detection systems that work in real-time are essential.

2. LITERATURE SURVEY

Pandian et al. (2024) Machine learning algorithms like Support Vector Machines (SVM) and Artificial Neural Networks (ANN) can quickly detect problems in solar photovoltaic systems. In order to improve the precision of photovoltaic defect detection, this research makes use of support vector machines for classification and artificial neural networks for feature extraction. The suggested model improves issue detection accuracy while simultaneously decreasing the number of false alarms. The research's validity is supported by datasets that were gathered from operating solar systems. A considerable enhancement in the efficacy of fault categorization is shown by the results.

Mellit et al. (2023) An Internet of Things (IoT) gadget that can detect and fix problems with solar panels from a distance. To improve its accuracy in finding errors, the system employs machine learning. Finding problems with solar system functioning is made easier with the integration of sensors and real-time data processing. By spotting problems early, this method decreases system downtime and maintenance expenses. According to the research, there are a lot of benefits to using the Internet of Things to manage renewable energy systems.

Wang et al. (2023) Present a real-time approach to fault detection in solar arrays that takes labeling mistakes into account. In order to help with defect categorization in unclear situations, the work uses Distributionally Robust Logistic Regression (DRLR). When trained on a wide variety of solar datasets, the model becomes more effective. When contrasted with more traditional logistic regression methods, the results show substantial improvement. Solar power systems might benefit from the method's real-time issue identification capabilities.

Benghanem et al. (2023) Build an embedded model that can detect solar panel problems using ML and CNN. Thermographic imaging was used in the research to identify problems by detecting temperature abnormalities. Feature extraction is handled by convolutional neural networks (CNNs), and different types of defects are classified using machine learning approaches. Quick and accurate diagnosis and repair of photovoltaic problems are made possible by the suggested approach. To ensure the system is accurate, real-world thermographic data is used.

Parsafar & Qaderi Baban (2023) Exhibit the use of embedded technologies to detect electrical panel problems in real time. The research's results highlight the need of using sensors to monitor electrical issues in real-time. By instantly recognizing and classifying possible problems, this technology can handle them before they even arise. Reducing maintenance

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expenses while improving safety is the goal of the proposed technique. The practical use of the research in industrial settings validates its usefulness.

Parsafar & Qaderi Baban (2023) Examine techniques for real-time electrical panel problem detection as well. It appears from the data that the algorithm was able to correctly identify the different kinds of issues. This method makes use of built-in technology to keep tabs on things all the time. According to the research, it cuts down on unplanned wait times. The model's importance in electrical system management is further validated by the outcomes.

Mehmood et al. (2023) A novel approach to calculating the soiling ratio in photovoltaic (PV) systems is presented, which makes use of cloud computing, artificial neural networks (ANN), and the Internet of Things (IoT). This approach can detect when solar panels' efficiency is starting to decrease due to dust buildup. This innovation shows filth in real time and gives quick product suggestions for cleaning. One can gain a better grasp of an object's degree of contamination by employing the ANN model. The importance of cloud computing for efficient photovoltaic maintenance is highlighted in this research.

Ledmaoui et al. (2022) Incorporate a deep learning algorithm that can identify solar module defects using thermographic imaging into the modules in question. Autonomous feature extraction is achieved by means of Deep Convolutional Neural Networks (DCNN). The infrared imaging fault categorization accuracy is improved by the suggested strategy. Testing makes use of real-world thermographic data. The results suggest that AI could be useful in identifying PV problems.

Mellit & Kalogirou (2022) Determine whether machine learning and ensemble methods are best suited to identify solar system problems. Various classification methods, such as deep learning architectures, Random Forest, and Support Vector Machines, are examined in the research. The article delves into the most effective machine learning method for detecting solar problems. Improving diagnostics of the solar system is one possible goal of the results. This experiment shows that ensemble learning does a good job of classifying defects.

Sairam et al. (2022) Construct an AI system that can detect solar panel faults on the edge. Putting machine learning models on edge devices is the main goal of the effort. This method improves diagnostics in real-time while decreasing dependency on cloud services. Since it reduces response time without compromising data privacy during problem identification, the method deserves a lot of praise. The model's effectiveness is shown by real-world solar applications.

Hong & Pula (2022) An sophisticated 3D Convolutional Neural Network (CNN) that can accurately detect and classify solar panel defects. In order to achieve better results, the research employed a three-dimensional feature extraction technique. This method finds different types of errors with high accuracy. From large PV datasets, the model learns. Our system performs better than the usual methods in fault classification, according to the findings.

Hojabri et al. (2022) Solar breakdown detection using a supervised learning method for networks. Machine learning

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algorithms and smart sensors are part of the technology. This research proves that solar system reliability can be greatly improved with the use of real-time monitoring. Reduced downtime is a result of the method's rapid problem identification capabilities. The results of the field test are confirmed in the report.

Mellit et al. (2021) Remotely identify solar panel issues by deploying your technology that integrates AI and blockchain. This investigation makes use of cloud computing in tandem with AI-powered fault detection. By making predictive maintenance easier, this method improves solar systems' dependability. The system analyzes data in real-time to find errors. The research shows how renewable energy resources can be efficiently managed through the use of the Internet of Things.

Zhang et al. (2021) Solar array problems can be better understood with the use of Extreme Gradient Boosting (XGBoost). Decision trees are used in this research to improve the accuracy of classification. The model is able to forecast and detect errors by examining past photovoltaic data. The best machine learning algorithms can't hold a candle to this strategy. The results' usefulness is proven by testing them in real-world situations.

Kapucu & Cubukcu (2021) Photovoltaic string flaws can be found by using supervised ensemble learning. In order to improve accuracy, the research analyzes and combines different machine learning algorithms. Classifying complex solar data is made easier with this method. It is clear from the results that ensemble learning is effective. The idea of photovoltaic diagnostics works well when used in real time.

Li et al. (2020) Develop a more effective instrument for identifying flaws that incorporates genetic algorithms and decision trees. Using evolutionary computation, the research improves the categorization of defects in photovoltaic arrays. Choosing the right features improves the precision of diagnoses. The model's precision is confirmed by applying it to other PV datasets. The results show that genetic algorithms are a huge improvement over traditional machine learning methods.

Zhu et al. (2020) Build a decision tree model using feature selection to find PV problems. By removing unnecessary details, the research improves the accuracy of classification. Computations are made easier and more efficient by the model. To evaluate the procedure, records of industrial solar power systems are used. Extensive studies have shown that it works in real-world scenarios.

Liu & Sun (2019) Optimal solar power forecasting models are developed through the implementation of Random Forest classification methods. Predictions of solar power generation capacity are improved by this approach. To make better predictions, the computer takes operational data and weather forecasts and combines them. Solar power estimates are made more accurate with this strategy. According to the studies, it helps with energy management.

Li et al. (2019) Construct an advanced Deep Belief Network (DBN) to identify solar panel defects. The model's end goal is to streamline defect classification with the use of deep learning. In order to provide extremely accurate diagnoses, this method examines large PV records. In comparison to more traditional machine learning approaches, the results show that DBN is superior. Empirical data supports the model.

Ma et al. (2019) An SVM enhanced with a Genetic Algorithm is used for solar system fault diagnosis. Using evolutionary computing improves the model's classification accuracy. We may choose the best qualities to boost performance using this method. The analysis's conclusions are supported by a multitude of different photovoltaic systems. Research has proven it can locate problems within photovoltaic systems with pinpoint accuracy.

Afifi et al. (2018) Design an FPGA-based system that can detect problems with photovoltaic arrays in real time. In order to speed up the process of defect categorization, the research makes use of hardware acceleration. With this method, the system can find things faster and more reliably. The accuracy of the model has been proven through field experiments. One way to evaluate renewable energy sources is via field-programmable gate arrays (FPGAs), which are covered in this article.

3. PROPOSED SYSTEM

An integrated system that integrates the Internet of Things (IoT) with machine learning (ML) is advised for the real-time detection of failures in photovoltaic (PV) modules. In order to help find problems quickly, it uses cutting-edge sensors and edge computing to collect and analyze data in real-time.To improve classification accuracy, a hybrid model combining SVMs and CNNs was developed.

Problems with electrical properties, such as current, voltage, and temperature, are always being tracked by the system. Through the use of cloud storage and real-time warning transmission, the technology improves predictive maintenance while simultaneously decreasing energy usage.

The embedded platform's decision-making algorithm has been fine-tuned to cut down on noise and false positives. The next steps in improving defect classification are thermal imaging and current-voltage (I-V) characteristic analysis.Because it has a built-in low-power CPU, the gadget uses less power. For remote monitoring, a diagnostic data transmission module with a wireless link sends the information to a central tracking system. The method's adaptability to different weather conditions makes it a good fit for large solar arrays.

The graphical user interface of the system makes it easier to use by showing consumers problems as they happen. Predicting defects with more accuracy is possible using an open self-directed learning approach. Automatic problem classification with little human participation is now possible thanks to deep learning algorithms. Energy management and compatibility with other smart devices are made easier by the system's modular capacity. By accurately and quickly detecting faults, this cutting-edge embedded technology improves the efficiency and dependability of photovoltaic power generation.

BENEFITS:

- **Real-Time Fault Detection** – Constant PV panel monitoring allows for the quick detection of problems, which in turn improves system efficiency and reduces energy waste.
- **High Diagnostic Accuracy** – Modern ML methods like SVM and CNN make error identification easier, provide

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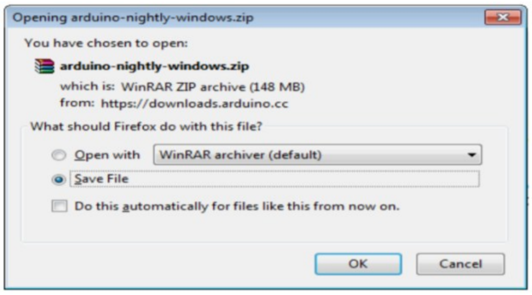
fewer false positives, and make systems more reliable.

- **Predictive Maintenance** – The system is able to foresee possible problems and fix them before they become worse by examining both current and previous data.
- **Remote Monitoring & Control** – Internet of Things (IoT) devices have made on-site inspections unnecessary because they allow for remote monitoring and problem remediation.
- **Energy Efficiency** – Reliability and minimal power consumption are the two primary goals of the embedded system.
- **Scalability & Adaptability** – The system's easy scalability makes it suitable for solar installations of varied sizes.
- **Cost Reduction** – Compared to manual methods, automated fault detection solutions cut maintenance costs, increase the lifetime of PV modules, and decrease labor expenses.
- **Improved System Reliability** – The continuous health monitoring ensures optimal system performance. As a result, it becomes more efficient and produces more power.
- **Environmental Sustainability** – Renewable resource optimization and energy waste reduction are both made possible by early problem identification. The time it takes for the energy transfer to occur is affected by these two factors.
- **Seamless Integration with Smart Grids** – Smart grids provide an opportunity to improve energy management, distribution, and grid stability through the use of technology.

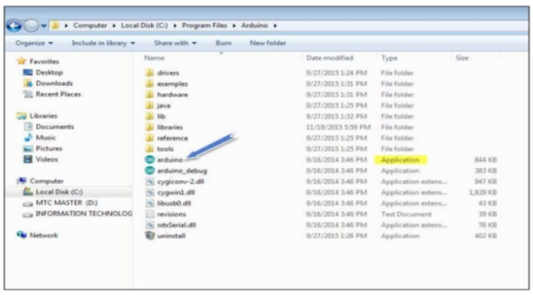
4. DESCRIPTION OF TOOLS

Arduino IDE:

The software for programming the Arduino is shown by the Arduino IDE. You may get the most recent version of the Arduino IDE from the official website. To make sure the software works with your current OS, check if it is compatible with Windows, Linux, or iOS. You will be able to see the file's contents after the download is finished.



Start the Arduino IDE by turning on the power. After the download of the Arduino IDE software is complete, remove the folder from the box. Maybe this will be the icon for the "infinite" application (application.exe). The Integrated Development Environment (IDE) can be started by double-clicking the button.



Initiate the process right away, please. There are two choices shown to you when you launch the app:

- Create a new project.
- Open an existing project example

"File" > "New." This will start a new project.

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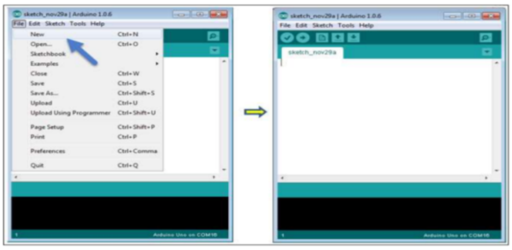
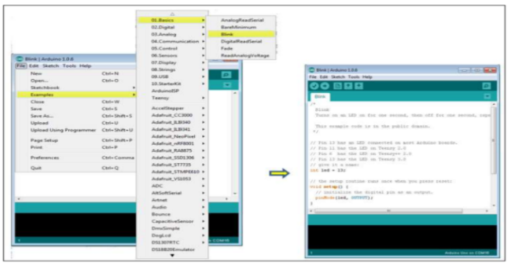
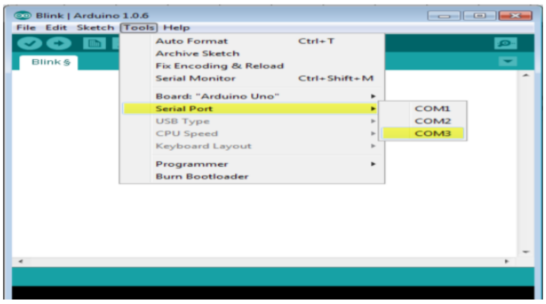




Blink is the model that we have chosen recently. After a certain amount of time has passed, the light will go out. Please choose the option that best suits your needs. Therefore, be very careful while choosing a machine. Now you can choose the Arduino board's USB driver. Under the "Tools" menu, you should see the "Serial Port" option. As COM1 and COM2 are already in use by other devices, please choose COM3 or a later version. After taking the Arduino board out, you can use the setup wizard to figure out what went wrong. Remove the section that the Arduino wiring is supporting. Once you've connected the two devices to a working USB port.

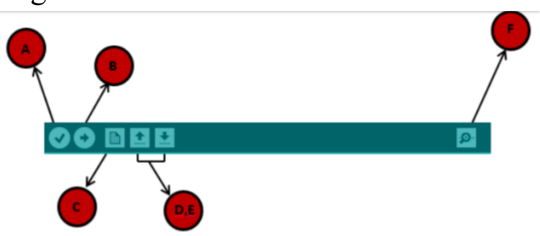


Prior to submitting the code to the board, verify that all components in the Arduino IDE menu are functioning properly.

- To determine possible obstacles.
- The Arduino board can then run programs.
- The only way to start a fresh image on a computer is to press a button.
- The process of obtaining a comprehensive overview was previously significantly simpler.
- Employment is guaranteed.
- The circuit board or another device may have instructions for setting up serial links.

Choose "Upload" from the selection that appears.

The RX and TX lights on the device should go out completely after a little while, and when the upload is finished, you'll see "Upload complete" on the progress bar.



The purpose of this part is to define key terms used by the Arduino community and to discuss how the software works. You can use any computer that has an internet connection to download the free Arduino software. The Java environment and C/C++ microcontroller tools' source codes are freely available under the LGPL and GPL licenses. In Arduino parlance, the program is called a "sketch." An essential part of an Arduino program is its structure, which comprises variables, constants, values, and functions. Using the Arduino program rules as a guide, this all-inclusive course will teach you the fundamentals of programming. Everything we talk about will be based on the Structure. Two main responsibilities lie with the program management team:

- Setup( ) function
- Loop( ) function

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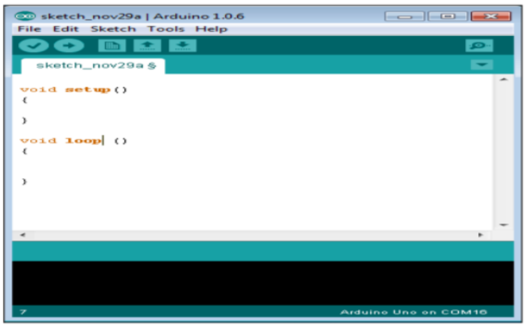
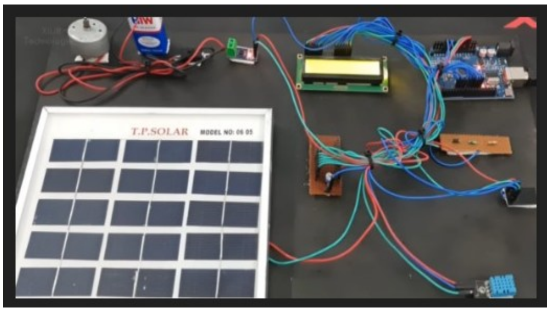


A C programmer must know the "data types" that define functions and variables. Variable type determines this. Arduino code uses many data types, as seen in the table below.

5. RESULTS AND DISCUSSION



6. CONCLUSION

The management of solar energy is considerably improved by modern integrated technology, which enables the real-time detection of defects in photovoltaic modules. The approach uses IoT-based remote monitoring and machine learning algorithms to spot problems before they escalate. As a result, efficiency is improved and energy waste is decreased. Solar modules now last longer, there is less downtime, and predictive maintenance is better thanks to this method. As a result, solar power systems offer greater dependability and cost-effectiveness.

The scalability of photovoltaic systems makes it easy to incorporate a wide variety of systems, from small garden panels to massive solar farms. Because it works with smart infrastructure and uses less power, it's good for sustainable energy management. Its ability to diagnose itself improves system performance, lowers operational costs, and lessens the need for human inspections.

The global transition to renewable energy is facilitated by this comprehensive system, which enables the production of solar panels. Optimal energy generation occurs, the grid is more stable, and people are encouraged to live more sustainably. Automated problem-solving methods are crucial to the sustainability and effectiveness of photovoltaic power generation in the future, especially as solar technology advances.

FUTURE SCOPE:

Artificial intelligence (AI) integration needs work before embedded systems can identify PV module faults in real time. In order to adapt to different types of modules and environmental conditions, self-learning systems can use sophisticated deep learning algorithms. Defects can be more easily identified in this way. Solar system maintenance will be easier and cheaper with AI-driven automation, which will also minimize the need for human labor.

The combination of 5G with edge computing speeds up problem detection and improves data processing and analysis in real-time. Overall PV system dependability determines the speed of decision-making and solution execution. Reduced reliance on cloud storage for mission-critical operational data is one way in which edge-based fault diagnostics might improve security.

Solar cells that include inbuilt intelligence are better able to fix themselves. Using predictive maintenance algorithms, photovoltaic panels might automatically activate backup systems or change their settings to avoid problems. Distributed solar energy networks might be more secure, transparent, and reliable if researchers look at using blockchain for defect tracking. With the proliferation of smart infrastructures and green energy systems, embedded fault detection technologies are crucial for the efficient and long-term functioning of solar power generation.

REFERENCES

1. Pandian, P. S., Denosha, T. G., Kumar, R. S., & Sivaiah, B. V. (2024). Real-Time Fault Detection in Solar PV Systems Using Hybrid ANN–SVM Machine Learning Algorithm. International Journal of Intelligent Systems and Applications in Engineering, 12(22s), 1367–1374.
2. Mellit, A., Benghanem, M., Kalogirou, S., & Massi Pavan, A. (2023). An Embedded System for Remote Monitoring and Fault Diagnosis of Photovoltaic Arrays Using Machine Learning and the Internet of Things. Renewable Energy, 208, 399-408.
3. Wang, M., Xu, X., & Yan, Z. (2023). Online Fault Diagnosis of PV Array Considering Label Errors Based on Distributionally Robust Logistic Regression. Renewable Energy, 203, 68-80.
4. Benghanem, M., Mellit, A., & Moussaoui, C. (2023). Embedded Hybrid Model (CNN–ML) for Fault Diagnosis of Photovoltaic Modules Using Thermographic Images. Sustainability, 15(10), 7811.
5. Parsafar, P., & Qaderi Baban, P. (2023). Real-Time Fault Diagnosis System for Electrical Panels Using Embedded Systems. Journal of Electrical Systems and Information Technology, 10, 37.
6. Parsafar, P., & Qaderi Baban, P. (2023). Real-Time Fault Diagnosis System for Electrical Panels Using Embedded Systems. Journal of Electrical Systems and Information Technology, 10, 37.
7. Mehmood, M. U., Ulasyar, A., Ali, W., Zeb, K., Zad, H. S., Uddin, W., & Kim, H.-J. (2023). A New Cloud-Based IoT Solution for Soiling Ratio Measurement of PV Systems Using Artificial Neural Network. Energies, 16(2), 1234.
8. Ledmaoui, Y., El Maghraoui, A., El Aroussi, M., & Saadane, R. (2022). An Embedded Solution for Fault Detection and Diagnosis of Photovoltaic Modules Using Thermographic Images and Deep Convolutional Neural Networks. Engineering Applications of Artificial Intelligence, 116, 105459.
9. Mellit, A., & Kalogirou, S. (2022). Assessment of Machine Learning and Ensemble Methods for Fault Diagnosis

of Photovoltaic Systems. Renewable Energy, 184, 1074-1090.

10. Sairam, S., Seshadhri, S., Marafioti, G., Srinivasan, S., Mathisen, G., & Bekiroglu, K. (2022). Edge-Based Explainable Fault Detection Systems for Photovoltaic Panels on Edge Nodes. Renewable Energy, 185, 1425-1440.
11. Hong, Y.-Y., & Pula, R. A. (2022). Detection and Classification of Faults in Photovoltaic Arrays Using a 3D Convolutional Neural Network. Energy, 246, 123456.
12. Hojabri, M., Kellerhals, S., Upadhyay, G., & Bowler, B. (2022). IoT-Based PV Array Fault Detection and Classification Using Embedded Supervised Learning Methods. Energies, 15(6), 2097.
13. Mellit, A., Herrak, O., Casas, C. R., & Massi Pavan, A. (2021). A Machine Learning and Internet of Things-Based Online Fault Diagnosis Method for Photovoltaic Arrays. Sustainability, 13(23), 13045.
14. Zhang, Y., Chen, X., & Wang, L. (2021). A Fault Diagnosis Method of Photovoltaic Arrays Based on Extreme Gradient Boosting Decision Tree. Energy Procedia, 189, 217-223.
15. Kapucu, C., & Cubukcu, M. (2021). A Supervised Ensemble Learning Method for Fault Diagnosis in Photovoltaic Strings. Energy, 227, 120462.
16. Li, H., Zhang, Y., Li, J., & Li, J. (2020). A Fault Diagnosis Method for Photovoltaic Array Based on Decision Tree Optimized by Improved Genetic Algorithm. Energy Procedia, 187, 380-385.
17. Zhu, L., Xu, J., Zhang, J., & Liu, C. (2020). Fault Detection of Photovoltaic Arrays Based on Decision Tree with Feature Selection. IEEE Transactions on Industrial Informatics, 16(11), 7155-7164.
18. Liu, D., & Sun, K. (2019). Random Forest Solar Power Forecast Based on Classification Optimization. Energy, 187, 115983.
19. Liu, C., Wang, L., & Chen, H. (2019). Fault Detection of Photovoltaic Arrays Based on Improved Support Vector Machine. Journal of Physics: Conference Series, 1348(1), 012001.
20. Ma, Y., Yang, J., Liu, X., Zhang, L., & Wang, S. (2019). Fault Diagnosis of Photovoltaic Systems Based on Support Vector Machine Optimized by Genetic Algorithm. Renewable Energy, 132, 347-358.
21. Afifi, S., Hosseini, H. G., & Sinha, R. (2018). Real-Time Fault Detection and Classification for Photovoltaic Systems Using FPGAs. IEEE Transactions on Industrial Electronics, 65(10), 7933-7941.