SMART ELECTRICITY CONSUMPTION MONITORING AND ANOMALY DETECTION SYSTEM

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Keywords:

Edge Machine Learning, IoT Energy Monitoring, Isolation Forest, Anomaly Detection, ESP32.

Introduction:

In standard Indian households, electricity usage remains a "black box" where users only see an aggregate monthly bill without granular data on individual appliances. This lack of visibility prevents the identification of malfunctioning devices, such as aging refrigerators or inefficient AC units, which often show "pre-failure" signs through subtle changes in power consumption long before failing. Existing commercial smart plugs often prioritize remote control over intelligent diagnostic capabilities. The SECMS addresses this by providing appliance-level visibility and real-time fault detection. By democratizing advanced energy diagnostics, this project empowers middle-class families and educational institutions to reduce wasteful consumption and prevent electrical fire risks. It aligns with national energy conservation goals by reducing overall stress on the local power grid.

Objectives:

1. To Develop a simple, low-cost smart plug using an ESP32 and PZEM-004T energy sensor to measure voltage, current, power, and energy of a single household appliance in real time, with the design kept modular so more plugs, cloud storage, and mobile apps can be added later.
2. To Build and train multiple machine-learning anomaly-detection models on the public home.csv household electricity dataset so they can reliably identify unusual appliance-level usage such as sudden spikes or abnormal running patterns.
3. To Compare these models in terms of detection accuracy, number of anomaly events flagged, and execution time, and select the one that offers the best trade-off between sensitivity and speed for real-time monitoring.
4. To Integrate the selected anomaly-detection model with the ESP32– PZEM-004T smart plug and a Wi-Fi-based Flask backend, providing a web dashboard where users can view live consumption, get instant alerts when behaviour looks abnormal, and review a log of past anomalous events.

Methodology:

The project utilizes a five-stage "Sense-Analyze-Act" pipeline to transform raw electrical signals into actionable safety alerts. The hardware follows a modular design, physically separating the high-voltage sensing domain (230V Mains) from the low-voltage logic domain (3.3V Microcontroller) for user safety.

- **Phase 1**: Collecting the Data The system starts by gathering electricity data from two places: a public dataset called home.csv (which shows normal household patterns) and live readings straight from the ESP32 smart plug connected to a real appliance. This mix helps the model understand both typical usage from history and exactly how your device behaves right now.
- **Phase 2:** Sending Data Over Wi-Fi the ESP32 takes each fresh sensor reading (voltage, current, power) and packs it into a tiny JSON message, then shoots it over Wi-Fi to the backend server using simple HTTP POST. If you need to check the dashboard from outside home, tools like ngrok can safely expose the API so data keeps flowing anywhere.
- **Phase 3:** Cleaning and Preparing Data Raw numbers coming in are messy, so we clean them up: fix missing or bad values, create useful patterns like moving averages or sudden power changes, and scale everything (voltage, current, power) so the model can compare them fairly.
- **Phase 4:** Spotting the Problems Clean data windows go into the chosen model (like Isolation Forest). For every batch of readings, it checks "Does this look normal based on what I learned, or is something weird?" and flags anything suspicious as an anomaly.
- **Phase 5:** Showing Results to User Finally, the backend pushes live readings + "normal/abnormal" labels to the web dashboard. Charts update in real time with Chart.js, pop-up alerts grab attention for spikes, and every anomaly gets logged with timestamp so you can review what happened when.

Result and Conclusion:

In conclusion, Testing confirmed that the Isolation Forest model outperformed LOF and OCSVM in residential settings, achieving a 96% detection rate with a fast 110ms execution time. In live field tests on the Indian 230V grid, the system accurately logged power spikes, such as a microwave door-open event jumping from 680W to 850W. The dashboard successfully visualized stable loads (e.g., a 9W LED bulb) as a flat blue line while instantly flagging controlled stress tests—such as adding a 700W load—with a "Toast Notification" containing freeze-frame data. A critical field result involved detecting a bearing jam in a fan motor, allowing for a fix four days before potential coil burnout, saving ₹1,800 in repairs. We concluded that edge-based AI is a viable, low-cost solution (under ₹5,000) for preventing equipment failure and reducing household energy waste

Project Outcome & Industry Relevance:

The primary outcome is a functional, low-cost "Smart Plug" prototype capable of autonomous fault detection. This project is highly relevant to the Indian residential sector, where voltage fluctuations and aging appliances contribute to high bills and fire risks. For industry, this demonstrates a scalable architecture for predictive maintenance that does not require expensive industrial SCADA systems. It provides a roadmap for appliance manufacturers to integrate "health-monitoring" features directly into hardware using TinyML

Working Model vs. Simulation/Study:

This project involved the development of a **physical working model**. The prototype consists of a custom-built smart plug integrated with an ESP32 and PZEM-004T sensor, housed in a fire-retardant ABS enclosure and validated against real household loads.

Project Outcomes and Learnings:

1. A working prototype of an IoT smart plug that can continuously monitor a household appliance and stream voltage, current, power, and energy data over Wi-Fi.
2. A validated anomaly-detection module that can flag sudden spikes, abnormal running patterns, or unusual standby consumption for the monitored appliance, along with quantitative comparison plots for different models.
3. A user-friendly web interface that provides secure login, real-time charts, pop-up alerts, and an event log, demonstrating how domestic users can gain appliance-level visibility and early fault indication using affordable hardware

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Future Scope:

The future scope of this project includes:

1. **Cloud Migration and Secure Communication:**
   The backend will be migrated from a local SQLite database to AWS IoT Core, replacing the current bandwidth-heavy HTTP POST requests with the lightweight MQTT protocol. This shift will implement a "Hot/Cold" storage architecture using Amazon DynamoDB for real-time rendering and Amazon S3 Glacier for long-term history, all secured via X.509 Certificate-based mutual authentication (mTLS).
2. **Mobile Application Development:**
   We intend to replace the web-based dashboard with a native mobile application built on Google Flutter, ensuring cross-platform support for both Android and iOS. This app will integrate Firebase Cloud Messaging (FCM) to deliver critical safety alarms that can override a smartphone's "Do Not Disturb" mode
3. **Edge Intelligence and Hardware Fail-safes:**
   By implementing TinyML via TensorFlow Lite for Microcontrollers, the Isolation Forest model will be quantized to run entirely within the ESP32's SRAM. This enables the smart plug to autonomously cut power during a fault even if Wi-Fi is unavailable, supported by a SIM800L GSM module as a secondary failover channel for dispatching critical SMS alerts.