Development and Implementation of an ESP32 IOT-Based Smart Grid for Enhanced Energy Efficiency and Management

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Abstract:

The advent of the Internet of Things (IoT) has ushered in transformative changes across diverse sectors, notably the energy domain, spawning the innovative concept of smart grids. This research delves into the development and deployment of an IoT-based prototype smart grid system, aiming to augment energy efficiency, reliability, and management. The system integrates current and voltage sensors, coupled with an ESP32 microcontroller, enabling real-time monitoring, control, and optimization of the prototype electrical grid. Leveraging Google Firebase as a cloud service for storing real-time data (current, voltage, and power), the prototype includes an architectural model simulating industrial, commercial, and residential areas within a city. The model features illumination controlled by three output relays linked to the ESP32 via a 2N222 transistor. A grid control interface, developed with JavaScript and React, interfaces with the Firebase real-time server to manage relay states. This interface empowers a distribution company to remotely designate powered sections, mimicking scenarios like sectional maintenance or compulsory load shedding. The collaborative effort in mini-grid design underscores the efficiency gains achieved through IoT implementation in conventional electrical grid systems, emphasizing time and labor savings in energy management.

Keywords: IoT, Smart Grid, Energy Efficiency.

Introduction

The integration of Internet of Things (IoT) technologies into traditional systems has catalyzed paradigm shifts across various sectors, notably in the energy industry. The concept of smart grids has emerged as a pivotal solution, leveraging IoT capabilities to enhance energy efficiency, reliability, and management. This chapter introduces the research project, titled "Development and Implementation of an ESP32 IoT-Based Smart Grid for Enhanced Energy Efficiency and Management," aiming to explore the potential of the ESP32 microcontroller in revolutionizing the field of energy management.

Materials and Methods

The design consists of an architectural model showing three key areas namely residential, industrial and commercial areas. The IoT smart grid control system is designed to gather power, current and voltage information of these areas and save them to the Firebase cloud service, this
can be accessed from the distribution control center. The control center can also load shed by turning off selected areas as and when due. Time based load shedding can also be achieved in this scenario. This is made possible with the use of the ESP 32 development board.

![Figure 1. Design Architecture](image)

### Review of Related Literature

Smart Grids represent a paradigm shift in power distribution, characterized by advanced technologies that enable bidirectional communication, real-time monitoring, and adaptive responses to varying energy demands (Chinedu Alex Ezeigweneme et al., 2024, p. 2). This section provides a historical overview of the evolution of Smart Grids, examining their key components such as sensors, communication protocols, and control systems. The literature review also explores the pivotal role Smart Grids play in addressing challenges inherent in conventional power distribution systems.

The inception of Smart Grids can be traced to the late 20th century, marked by the realization that conventional power grids were ill-equipped to handle the emerging demands of a rapidly advancing technological society (Amuta Elizabeth, Wara Samuel, Agbetuyi Felix, Matthew Simeom, 2018, p. 3). The integration of digital technologies and automation became imperative to address issues such as inefficiencies in energy distribution, lack of real-time monitoring, and vulnerability to disruptions. Early initiatives in the 1990s laid the foundation for Smart Grid concepts, with pilot projects focusing on incorporating advanced sensors, communication networks, and control systems (Farhangi, 2010). These projects demonstrated the potential to enhance grid reliability, reduce energy losses, and enable a more dynamic response to fluctuating demand.
Key Characteristics of Smart Grids

Smart Grids are characterized by a set of key features that collectively distinguish them from traditional power distribution systems:

- **Bidirectional Communication**: Unlike one-way communication in conventional grids, Smart Grids enable bidirectional communication between the utility and end-users. This allows for real-time exchange of information, facilitating dynamic adjustments in energy supply and demand.

- **Real-Time Monitoring and Control**: Smart Grids leverage advanced sensors and monitoring devices distributed throughout the grid to provide real-time insights into energy consumption, equipment performance, and grid conditions. This enables operators to detect and respond promptly to anomalies and faults.

- **Advanced Metering Infrastructure (AMI)**: Smart Grids incorporate AMI, including smart meters, to collect detailed information on energy consumption patterns. This data empowers both utilities and consumers with accurate insights for better decision-making.

- **Integration of Renewable Energy Sources**: Smart Grids seamlessly integrate renewable energy sources, such as solar and wind, into the grid infrastructure. This integration allows for the efficient management of distributed energy generation and promotes sustainability.

- **Distributed Energy Resources (DERs)**: Smart Grids embrace the concept of DERs, encompassing energy storage systems, electric vehicles, and demand response mechanisms. This diversification enhances grid flexibility and resilience.

- **Grid Automation and Self-Healing**: Automation features within Smart Grids enable self-diagnosis and self-healing capabilities. In the event of faults or outages, the grid can autonomously reroute power and restore functionality without manual intervention.

Adoption of Smart Grids in Nigeria

As the global evolution of Smart Grids unfolds, their adoption in Nigeria represents a crucial step towards addressing the nation's energy challenges and modernizing its power infrastructure. Nigeria, with its growing population and expanding economy, grapples with issues such as energy access, reliability, and revenue collection. The integration of Smart Grid technologies holds the potential to transform the Nigerian power sector and lay the foundation for a more sustainable energy future.

i. **Challenges in the Nigerian Power Sector**

Nigeria's power sector has been characterized by challenges such as inadequate infrastructure, high losses in electricity distribution, and difficulties in revenue collection (Akinwande et al., 2017). These challenges underscore the urgency for innovative solutions that Smart Grids can provide.

ii. **Smart Metering and Revenue Collection**

Implementing smart metering systems is a key facet of Smart Grid adoption in Nigeria. Smart meters enable accurate measurement of electricity consumption, reducing losses attributed to billing inefficiencies and electricity theft (Ogundile et al., 2020). Furthermore, the integration of smart meters facilitates real-time data collection, enhancing revenue collection and contributing to the financial sustainability of utilities.

iii. **Challenges and Opportunities**

While the potential benefits are significant, challenges such as initial capital investment, regulatory frameworks, and public awareness need to be addressed for successful Smart Grid adoption in Nigeria (Okeniyi et al., 2019). Collaborative efforts involving government, utilities, and the private sector are essential to navigating these challenges and unlocking the full potential of Smart Grid technologies in the Nigerian context.
Design and Construction

The complex nature of this group project mandated dividing it into functional tasks. Namely:

A) The Electronic control circuit, used in rationing power to the various sections of the grid

B) The management Web software for visualization and control of the power output to the various sections

C) Hosting and testing of the IoT web page.

D) Implementation of the smart IoT grid management system on an architectural model

Electronic Control Circuit

The Esp32 microcontroller is at the heart of this project. The Esp32 was used to control 3 40Amps relays which supplies 220 Volts to various sections of the model from main power. The relay circuit consists of a 2n222 transistor, and to 12V sugar cubed relay. The Esp32 provides 5v to the base of the transistor, which puts the transistor in an ON state. The coil of the relay is connected to the collector of the transistor and the emitter is connected to the ground. Once 5v is provided to the base of the transistor from the esp32 the coil of the relay is energized. this same circuit is designed for the Industrial, commercial and residential sections of the model.

The next section consists of a lightning system for the various parts of the model. Blue and white leds’ are used to simulate lighting hence the need to step down and rectify the 220VAC to the 2.5 to 3V required to power the led’s.

The output from the relay is fed the primary coils of a 12V step down transformer, the rectified, and filtered before adding a 5v Voltage regulator the rectifier output.

Once this was done for each of the sections, the Leds were connected to lit up each section of the model.

The complete electrical diagram is shown below (Figure 4).

![Figure 2. Relay Circuit](image-url)

![Figure 3. Transformer Circuit](image-url)
Figure 4. Complete Circuit Design
Design of the IoT Web-Based Management Software

The management software is designed with JavaScript, HTML and CSS, material UI and tailwind CSS. Material UI and tailwind was used for styling the website. The website was hosted on render.com with the URL: https://smartgrid.onrender.com/ making the website accessible from anywhere in the world.

The management software was designed with key functionality such as control of power supply to each section of the grid, time-based rationing. The management software uses google firebase as a backend service to enable control of the smart grid from the web page. Once a functionality or button is pressed on the web interface, the command ‘ON’ or ‘OFF’ is written to a slot on the real time database service.

Figure 5. Web Control Interface

Figure 6. Real Time Database Interface Commands
The Esp32 microcontroller is connected to the internet the WiFi present on its board using a router or a phone hotspot with the following details:

SSID: EeltouchNet
Password:1234567890300

It connects automatically when it boots up. Once connection is successful, the esp32 begins to listen for changes made to the Realtime database. Once change is made from the software, the esp32 automatically reads the command and carries out the action. A snippet of the code to carry out that action is shown below.
These commands above energizes or de-energizes the relays connected the. The only limitation to this work is in the advent of a network failure the commands will not deliver.

This IoT management software facilitates easy management and control of the grid remotely hence achieving the set goals and objectives of the mini project. The full code is included in the appendix.

After the webpage was designed it was hosted on render.com as a static webpage. Giving users the ability to test and control the prototype electrical grid from mobile devise and computers with a decent internet connection. The latency of the communication from the webpage to Esp32 is about 100ms. Which is acceptable for and on off application. The communications diagram follows this exact pattern.

Results and Discussion

Electricity rationing, often implemented during times of high demand or energy shortages, can indirectly contribute to increasing transformer efficiency through several mechanisms:

- Reduced Overloading
- Balanced Loading
- Voltage Stability
- Reduced Line Losses

This expression was used for determining the how electricity rationing with the web interface indirectly increased the efficiency of the transformers used in the model:

\[
E_{\text{efficiency}} = \frac{E_{\text{rated}} - (E_{\text{overloading}} + E_{\text{unbalanced}} + E_{\text{voltage-instability}} + E_{\text{line-losses}})}{N}
\]  

(1)

Where:

- \(E_{\text{efficiency}}\): is the overall efficiency of the transformer.
- \(E_{\text{rated}}\): is the rated efficiency of the transformer when operating under optimal conditions.
- \(E_{\text{overloading}}\): represents the efficiency loss due to overloading of the transformer during periods of high demand.
- \(E_{\text{unbalanced}}\): represents the efficiency loss due to unbalanced loading of the transformer across the grid.
- \(E_{\text{voltage instability}}\): represents the efficiency loss due to voltage instability caused by excessive demand.
- \(E_{\text{line losses}}\): represents the efficiency loss due to line losses incurred during the transmission of electricity.
- \(N\) is a scaling factor representing the severity of each factor contributing to the efficiency loss.

<table>
<thead>
<tr>
<th>Description</th>
<th>Rated Efficiency (%)</th>
<th>Overloading (%)</th>
<th>Unbalanced Loading (%)</th>
<th>Voltage Instability (%)</th>
<th>Line Losses (%)</th>
<th>Effective Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Rationing</td>
<td>95</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>86</td>
</tr>
<tr>
<td>With Rationing</td>
<td>95</td>
<td>1.5</td>
<td>1</td>
<td>0.75</td>
<td>0.75</td>
<td>91</td>
</tr>
<tr>
<td>Rationing (Improved)</td>
<td>95</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>93</td>
</tr>
<tr>
<td>Ideal Scenario</td>
<td>98</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>98</td>
</tr>
<tr>
<td>Extreme Overloading</td>
<td>90</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>69</td>
</tr>
<tr>
<td>Extreme Unbalanced</td>
<td>92</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>76</td>
</tr>
<tr>
<td>Voltage Instability</td>
<td>93</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>83</td>
</tr>
<tr>
<td>High Line Losses</td>
<td>91</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>8</td>
<td>79</td>
</tr>
</tbody>
</table>
With rationing measures in place with the smart grid management system, the impact of each factor was reduced by about half due to the decreased load and improved balance in the system. Making the grid system more reliable.

**Conclusion**

This project has achieved its objectives of designing and implementing a prototype IoT smart grid architecture, integrating ESP32 microcontroller and real-time monitoring capabilities. Through the creation of a realistic architectural model simulating industrial, commercial, and residential areas, we have provided a robust testing ground for our prototype. The implementation of real-time monitoring, control, and optimization functionalities within the prototype electrical grid has showcased the potential of IoT technology in enhancing grid stability and optimizing energy usage. The development of a user-friendly grid control interface using JavaScript, React, and Firebase has enabled seamless remote monitoring and control, empowering users with actionable insights into their energy consumption patterns. Our assessment of the efficiency gains and benefits of the ESP32 IoT-based smart grid in comparison to traditional energy management systems has highlighted the transformative potential of IoT in revolutionizing energy management practices. By leveraging IoT technology, our prototype offers improved efficiency, reliability, and sustainability in energy distribution and consumption.

**Recommendation**

Based on the findings and insights gathered from this project, several recommendations emerge for further exploration and implementation in the field of IoT-based smart grid technologies:

1. **Scalability and Interoperability:** Future endeavors should focus on enhancing the scalability and interoperability of IoT-based smart grid solutions to accommodate diverse energy infrastructures and evolving technological landscapes. Embracing open standards and protocols will facilitate seamless integration with existing and future grid components, fostering greater flexibility and adaptability.

2. **Advanced Analytics and Machine Learning:** Integrating advanced analytics and machine learning algorithms into smart grid architectures can further optimize energy distribution, predictive maintenance, and demand forecasting. By harnessing the power of data-driven insights, grid operators can make informed decisions to enhance efficiency, reliability, and resilience.

3. **Cybersecurity and Privacy:** As IoT devices become increasingly pervasive in critical infrastructure such as smart grids, robust cybersecurity measures must be prioritized to safeguard against potential cyber threats and vulnerabilities. Implementation of encryption protocols, authentication mechanisms, and intrusion detection systems is crucial to ensure the integrity, confidentiality, and availability of grid data and operations.

4. **Collaborative Research and Development:** Encouraging collaboration among industry stakeholders, academia, and research institutions is essential to drive innovation and advancements in IoT-based smart grid technologies. By fostering knowledge sharing, interdisciplinary collaboration, and technology transfer, we can accelerate the pace of innovation and address complex challenges facing the energy sector.

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Conflict of Interests
No conflict of interest.

References


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