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Study of Distributed Power Flow Control Scheme in Microgrid with Quality of Energy Services

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The increasing demand for reliable, decentralized, and renewable-based energy systems has brought Direct Current (DC) microgrids (MGs) into the spotlight, particularly for remote, rural, and disaster-prone regions. DC MGs offer simplified integration of photovoltaic (PV) sources, energy storage systems (ESS), and DC loads by eliminating conversion losses typical in AC systems. However, real-world implementation of such systems remains limited, with most prior research focused solely on simulations and theoretical control strategies. It typically integrates various energy sources, including RESs, conventional energy sources, and energy storage systems (ESSs) in a distributed manner. However, designing safe and reliable MG involves complex challenges due to the diverse power criteria problems and interactions of RESs, ESSs, and energy loads, and the variable and intermittent nature of RESs and energy loads.

The thesis begins by presenting the evolution and significance of MGs, emphasizing the global transition from centralized to decentralized energy systems. The first chapter outlines the historical background of MGs, tracing their emergence as a solution for integrating RES like solar PV systems and storage units into local power networks. It highlights the need for autonomous, resilient, and efficient control mechanisms within MGs, especially in rural, remote, or disaster-prone areas. The motivation for this study stems from limitations in current DC MG designs, particularly the absence of real-time load prioritization, SoC-based power sharing, and experimental validation of control strategies. The research problem is clearly defined as the challenge of managing power flow from multiple ESS units to heterogeneous loads with varying priority levels. To address this, the study proposes a SoC-based Power Assignment (SPA) algorithm and introduces a small-scale DC MG testbed for experimental verification. The chapter also states the research objectives, outlines the major contributions, and summarizes the thesis structure.

This thesis presents the architecture, system model, and algorithmic framework of the proposed DC microgrid (MG). It opens with an introduction to the real-world challenges that informed the design of the testbed, particularly the integration of smart and traditional loads, ESS, and renewable sources like PV units. The proposed system architecture is developed to reflect a practical, scalable DC MG with distributed energy flow. A dedicated subsection outlines the strategic placement of measurement points throughout the MG to monitor parameters such as voltage, current, power, and SoC, which are critical for both control logic and performance evaluation. The component-level breakdown discusses the functionality and role of each hardware unit, including PV generation, ESS units, critical and non-critical loads, and external controllers. The communication protocol design is described with a focus on MQTT and HTTP APIs for low-latency, reliable messaging between Raspberry Pi-based local controllers and a central main controller. This protocol ensures timely decision-making, especially under constrained energy conditions. The heart of the chapter lies in the SoC-based Power Assignment (SPA) algorithm, which dynamically allocates power from ESS to loads based on current SoC levels, energy demand, and the Quality of Energy Services (QoES) priorities. The algorithm incorporates safety bounds and promotes SoC balancing between multiple ESS units, mitigating the risk of rapid depletion or system imbalance. Additional submodules such as physical constraints, software design, and logical device interconnections are detailed to highlight the robustness and adaptability of the system.

Furthermore, the QoES framework extends to both power flow control and communication layers, ensuring not only the prioritization of critical loads but also reliable message execution in real time. Finally, the simulation environment is developed in Python using real PV and load data to validate the algorithm prior to hardware implementation. The simulation results confirm the benefits of the SPA algorithm in improving SoC balance, reducing energy loss, and maintaining voltage stability thereby bridging theoretical control strategies with real-world feasibility.

This thesis presented the complete experimental implementation of the proposed SPA-based DC microgrid system. The experimental environment was established using real hardware, including photovoltaic (PV) generation units, dual ESS1 and ESS2, and a variety of smart and traditional power loads such as Glacier, Airwave, electric kettle (EK), and rice cooker (RC). A modular architecture was designed to ensure flexible and scalable deployment of the testbed components. The hardware configuration outlined the integration of key components, emphasizing the use of Raspberry Pi modules as control interfaces, MOSFET switches for traditional load switching, and sensors such as the PZEM-017 for power monitoring. The DC bus design focused on safe, efficient interconnection, employing XT60 connectors and 12 AWG cabling to manage power delivery across the microgrid.

To ensure real-time control and communication, external controllers were developed for both ESS and load units. These controllers interfaced with a centralized main controller using MQTT and HTTP protocols, enabling prioritized power assignment based on SoC and QoES logic.

The experimental procedure section detailed the challenges encountered during the physical implementation, including synchronization issues during dual-ESS operation and control integration with mixed-type devices. These were mitigated through adaptive control strategies and hardware-software coordination.

Finally, the chapter presented and analyzed experimental results showing the power sharing behavior, voltage stability on the DC bus, and individual device performance under SPA algorithm control. The findings validated that the proposed architecture achieved its design objectives: stable power delivery, balanced SoC across ESS units, prioritized load management, and overall system robustness under dynamic real-world conditions.

This research presents several novel contributions that collectively advance the state-of-the-art in DC microgrid development and control. Firstly, it goes beyond simulation by experimentally developing a fully functional small-scale DC microgrid testbed, integrating PV generation, dual ESS units, smart and non-smart loads, and centralized control logic. Unlike traditional systems where loads passively consume energy, this work introduces an active power assignment mechanism through a SoC-based Power Assignment (SPA) algorithm that intelligently distributes power from ESS to prioritized loads based on system conditions. Another significant contribution is the real-time implementation of SoC balancing between multiple ESS units a feature previously explored only in simulation which enhances operational safety, system reliability, and extends ESS lifetime. Furthermore, the SPA algorithm enables adaptive load management under fluctuating power conditions; when generation (PG_j) is less than demand (PL_k), the system applies QoES-based prioritization to sustain critical services. Finally, the research develops an integrated communication framework that bridges smart devices (e.g., Glacier, Airwave) and non-smart appliances (e.g., electric kettle, rice cooker) using MQTT and HTTP protocols, enabling reliable and prioritized data exchange for both control and monitoring purposes.

Collectively, this work offers a validated framework for implementing adaptive power management in small-scale DC microgrids. The proposed approach can serve as a foundational model for future studies involving mobile energy storage, autonomous scheduling, and scalable control systems for larger, more complex microgrid environments.

Keywords: DC Microgrid, Power Flow Control, Power Assignment Algorithm, Energy Management, Energy Storage System (ESS), Quality of Energy Services (QoES), Communication Protocol