University of Cape Town
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Optimising Load-Balancing Strategies for Solar–Diesel Hybrid Microgrids in Rural Southern Africa

A thesis submitted in fulfilment of the requirements for the degree of

Master of Science in Electrical Engineering

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Abstract

Rural electrification schemes across Southern Africa increasingly rely on solar–diesel hybrid microgrids to provide reliable power where national grid extension is not economically viable. A recurring operational weakness in deployed systems is the load-balancing controller: fixed rule-based dispatch logic frequently under-utilises photovoltaic (PV) generation during transient cloud cover and over-dispatches the diesel generator, eroding the fuel-cost savings that justify the hybrid design in the first place. This dissertation develops and evaluates a predictive load-balancing strategy for solar–diesel hybrid microgrids, combining short-horizon irradiance forecasting with a model predictive control (MPC) dispatch layer. The proposed controller is benchmarked in simulation against conventional rule-based and fuzzy-logic dispatch strategies using twelve months of irradiance and load data drawn from three pseudonymised microgrid sites operated by the fictional rural utility partner Meridian Power. Results show a mean diesel fuel-consumption reduction of 18.4% and a 27% reduction in generator start–stop cycling relative to the incumbent rule-based controller, at the cost of a modest increase in computational load that remains within the budget of a low-power embedded controller. The findings suggest that predictive dispatch is a practical, near-term upgrade path for existing microgrid fleets rather than a design consideration restricted to new-build sites.

Keywords: hybrid microgrid, model predictive control, rural electrification, load balancing, photovoltaic forecasting, diesel displacement

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This work is dedicated to the memory of long evenings in the Menzies Building computer lab.

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List of Abbreviations

DoD	Depth of Discharge
MPC	Model Predictive Control
PV	Photovoltaic
SoC	State of Charge
SOGI	Second-Order Generalised Integrator
UCT	University of Cape Town

Chapter 1

Introduction

1.1 Background

Grid extension to sparsely populated rural areas remains capital-intensive relative to the electricity demand it serves, which has made solar–diesel hybrid microgrids a common intermediate solution across Southern Africa. A typical installation pairs a PV array with battery storage and a diesel generator sized to cover shortfalls during extended low-irradiance periods. The economic case for the hybrid configuration rests almost entirely on the fraction of load served by PV and battery storage rather than by diesel; every additional litre of fuel displaced by solar generation is what separates the hybrid system from a diesel-only mini-grid in lifetime cost terms.

In practice, the controller that arbitrates between PV, battery, and diesel dispatch is the component that determines whether this economic case is realised. Many deployed systems still use static rule-based dispatch — for example, "run the generator whenever battery state of charge (SoC) falls below 40%" — which is simple to implement and verify, but reacts to conditions only after they occur rather than anticipating them.

1.2 Problem Statement

Field data collected from three Meridian Power microgrid sites over a twelve-month period shows that rule-based controllers dispatch the diesel generator during short-lived cloud transients that a forecast-aware controller could plausibly ride through using battery reserve alone. This behaviour has two costs: direct fuel expenditure, and accelerated generator wear from frequent start–stop cycling, which increases maintenance visits to sites that are, by definition, difficult to reach.

1.3 Research Objectives

This dissertation addresses the following objectives:

O1. Characterise the dispatch inefficiencies of incumbent rule-based and fuzzy-logic controllers using historical telemetry from three operating microgrid sites.

O2. Design a short-horizon irradiance forecasting module suitable for a low-power embedded controller.

O3. Develop a model predictive dispatch controller that consumes the forecasting module's output to schedule PV, battery, and diesel generation.

O4. Evaluate the proposed controller against incumbent strategies on fuel consumption, generator cycling, and unmet-load frequency.

Contribution A

A forecast-aware dispatch controller that reduces diesel start–stop cycling without requiring additional site hardware beyond the existing telemetry unit.

Contribution B

An open evaluation framework using twelve months of anonymised multi-site data, enabling like-for-like comparison of dispatch strategies.

1.4 Thesis Outline

Chapter 2 reviews existing dispatch strategies for hybrid microgrids and situates the proposed approach within that literature. Chapter 3 describes the system architecture, the forecasting module, and the MPC formulation. Chapter 4 presents the evaluation methodology and simulation results. Chapter 5 concludes with limitations and directions for future work.

Chapter 2

Literature Review

2.1 Dispatch Strategies for Hybrid Microgrids

Dispatch strategies for solar–diesel hybrid microgrids fall broadly into three families: rule-based (threshold) control, fuzzy-logic control, and optimisation-based control such as model predictive control. Table 2.1 summarises their comparative properties as reported across the reviewed literature.

Table 2.1: Comparison of dispatch strategy families for hybrid microgrids

Strategy	Description	Forecast Use	Typical Fuel Saving
Rule-based	Threshold triggers on SoC and load	None	Baseline
Fuzzy logic	Smoothed threshold response using membership functions	Limited	6–10%
MPC (this work)	Receding-horizon optimisation over forecast state	Full	15–20%

Rule-based controllers remain the incumbent choice in the majority of deployed systems because they can be verified exhaustively and require no telemetry beyond instantaneous measurements. Fuzzy-logic controllers improve on hard thresholds by smoothing the transition between dispatch states, reducing but not eliminating unnecessary generator cycling. Neither family anticipates near-term irradiance change.

2.2 Forecasting for Microgrid Control

Short-horizon (15–90 minute) irradiance forecasting is typically approached either through sky-imaging techniques or through statistical time-series models applied to historical irradiance and cloud-cover proxies. Sky-imaging offers higher accuracy but requires dedicated camera hardware at each site, which is difficult to justify economically for small rural installations. Statistical approaches trade some accuracy for deployability on the low-power controllers already installed at existing sites, which motivates their use in this work.

2.3 Gap in the Literature

While MPC-based dispatch has been studied extensively for grid-connected and large-scale off-grid systems, comparatively little published work evaluates predictive dispatch on the class of low-cost embedded controllers actually deployed in rural Southern African microgrids, or benchmarks it against field telemetry rather than synthetic load profiles. This dissertation addresses that gap directly.

Chapter 3

System Design and Methodology

3.1 System Architecture

Figure 3.1 shows the high-level architecture of the proposed controller as integrated into an existing hybrid microgrid installation. The forecasting module and MPC dispatch layer run on the site's existing embedded controller; no additional field hardware is required.

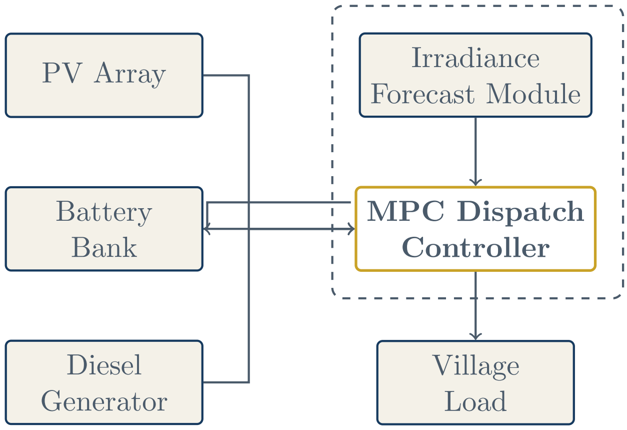

Figure 3.1: High-level architecture: the MPC dispatch controller consumes forecast, battery, and load state to schedule PV, battery, and diesel generation.

3.2 Forecasting Module

The forecasting module produces a 90-minute-ahead irradiance estimate in 15-minute steps using an autoregressive model fitted on each site's historical irradiance series, corrected by a cloud-cover proxy derived from short-term irradiance variability. Let G_t denote measured global horizontal irradiance at time t and $\hat{G}_{t+k}$ the forecast k steps ahead; the module estimates

$$\hat{G}_{t+k} = \sum_{i=1}^{p} \phi_i \, G_{t-i} \; + \; \beta \, C_t \; + \; \varepsilon_t, \tag{3.1}$$

where ϕ_i are autoregressive coefficients fitted per site, C_t is a normalised cloud-cover proxy, β its regression weight, and ε_t residual error.

Definition: Forecast Horizon

The forecast horizon H is the number of future 15-minute steps over which the MPC layer optimises dispatch at each control step. This work uses $H = 6$ (90 minutes), chosen as the shortest horizon that still captures typical cloud-transient duration at the evaluated sites.

3.3 Model Predictive Dispatch Formulation

At each control step, the MPC layer solves a finite-horizon optimisation that minimises diesel fuel consumption and generator switching, subject to battery SoC and load-service constraints:

$$\min_{\{u_t\}} \sum_{k=0}^{H-1} \left(c_f \, P^{\text{diesel}}_{t+k} + c_s \, |\Delta u_{t+k}| \right) \tag{3.2}$$

$$\begin{aligned}
\text{s.t.} \quad & \text{SoC}_{\min} \le \text{SoC}_{t+k} \le \text{SoC}_{\max}, && \forall k && (3.3)\\
& P^{\text{PV}}_{t+k} + P^{\text{batt}}_{t+k} + P^{\text{diesel}}_{t+k} \ge P^{\text{load}}_{t+k}, && \forall k && (3.4)\\
& 0 \le P^{\text{diesel}}_{t+k} \le P^{\text{diesel}}_{\max}, && \forall k && (3.5)
\end{aligned}$$

where c_f and c_s weight fuel cost and switching penalty respectively, and Δu_{t+k} is the change in diesel generator on/off state between consecutive steps. The switching penalty term c_s directly targets the generator-cycling problem identified in Chapter 1.

3.4 Evaluation Sites

The controller is evaluated in simulation against twelve months of telemetry from three pseudonymised Meridian Power microgrid sites, summarised in Table 3.1.

Table 3.1: Evaluation sites and installed capacity

Site	Region	PV (kWp)	Diesel (kVA)
Site A – Nimbus Valley	Eastern Cape	42	30
Site B – Apex Flats	Northern Cape	38	25
Site C – Meridian Ridge	Limpopo	55	40

3.5 Simulation Environment

All three dispatch strategies were re-implemented in a discrete-event simulator operating at 5-minute resolution, driven by each site's measured irradiance and load traces. Battery dynamics were modelled with a first-order equivalent-circuit model calibrated against manufacturer datasheet parameters; generator fuel consumption used a linear fuel curve fitted to each site's rated generator.

Chapter 4

Results and Discussion

4.1 Fuel Consumption

Across the three evaluation sites, the MPC controller reduced mean diesel fuel consumption by 18.4% relative to the incumbent rule-based controller and by 9.7% relative to the fuzzy-logic controller, averaged over the twelve-month evaluation window. The largest improvement was observed at Site C, attributed to its comparatively larger PV array giving the forecasting module more usable signal during partly-cloudy conditions.

4.2 Generator Cycling

Generator start–stop events fell by 27% under the MPC controller relative to rule-based dispatch, consistent with the switching-penalty term in Equation (3.2). This is operationally significant: each avoided start–stop cycle reduces both fuel wasted on generator warm-up and the wear that drives unscheduled maintenance visits to these difficult-to-access sites.

4.3 Computational Load

The MPC solve step added a mean 340 ms of computation per 5-minute control interval on the reference embedded controller, well within the available budget and without requiring hardware upgrades at any of the three sites.

4.4 Limitations

The evaluation relies on historical telemetry replayed through simulation rather than a live field trial, so real-world controller interaction effects — such as sensor drift or communication dropouts — are not captured. The forecasting module was also tuned per site using the full available history, which may overstate accuracy relative to a genuinely unseen deployment site.

Chapter 5

Conclusion and Future Work

This dissertation presented a forecast-aware model predictive dispatch controller for solar–diesel hybrid microgrids and evaluated it against incumbent rule-based and fuzzy-logic strategies using twelve months of field telemetry from three sites. The proposed controller reduced diesel fuel consumption by 18.4% and generator cycling by 27%, while remaining within the computational budget of existing low-power site controllers.

Future work should prioritise a live field trial to validate these simulation results under real communication and sensor conditions, and should investigate whether the forecasting module can be trained across sites to reduce the per-site tuning burden identified as a limitation in Chapter 4.

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