Optimal design of rural mini-grids operated by a rolling-horizon strategy: a method to reduce computational requirements

Davide Fioriti*, Giovanni Lutzemberger*, Davide Poli*, Andrea Micangeli† and Pablo Duenas-Martinez‡
* DESTEC, University of Pisa
Largo Lucio Lazzarino, 56122 Pisa, Italy
Email: davide.fioriti@ing.unipi.it
† DIMA, University of Rome "Sapienza"
Via Eudossiana 18, 00184 Roma, Italy
Email: andrea.micangeli@uniroma1.it
‡ MITEI, Massachusetts Institute of Technology
77 Massachusetts Avenue, 02139 Cambridge, MA, United States
Email: pduenas@mit.edu

***Abstract*—Reducing costs and risks to foster rural electrification in developing countries is one of the major hurdles for researchers, firms and practitioners aiming to develop business with rural mini-grids, which are local networks that supply energy demand by exploiting local sources. Predictive rolling-horizon operating strategies have proven to reduce operating costs and better cope with uncertainties in renewable sources and demand than standard priority-list approaches, when forecasts are accurate enough. Their main drawback is the need for more powerful controlling devices, which, however, is becoming acceptable for modern operation purposes. Yet, calculating the optimal design of the mini-grid operated with predictive strategies can easily require much larger computational requirements than with priority-list rules. In the present paper, we describe a two-stage procedure to reduce the computational requirements of design methodologies based on predictive strategies. First, an optimization is developed using a priority-list strategy, namely load-following, whose results are used to refine the second-stage optimization based on an advanced rolling-horizon strategy. Results suggest significant reduction in computational requirements, up to -84% with respect to standard predictive approaches, with negligible reduction in the optimality of results.**

***Index Terms*—off-grid energy system; isolated hybrid system; optimization; MILP; micro-grid**

I. INTRODUCTION

Mini-grids, which are systems able to supply electricity through a local network even disconnected by the national grid, have risen attention in recent years since they can foster rural electrification in developing countries without incurring in the high costs of extending the national grid in remote areas [1]. Access to electricity is also an important driver of rural development [2], but yet about a billion people still lacks of any service [3], mostly in rural areas of Sub-Saharan countries. The high risks and limited revenues are important barriers for the widespread of mini-grids, thus efficient design and system operation must be achieved.

Typical mini-grids exploit local sources, mainly renewable energy, in order to reduce reliance on fuel generators but guarantee a good quality of supply [4]; storage systems are often required to meet the peak demand and shift the energy produced to hours of high load. However, fuel-based generators are often used to guarantee the service in durable periods of low renewable energy production.

As firstly discussed in [5], the main methods to operate mini-grids are the Load-Following Strategy (LFS), the Cycle-Charging (CCS), and predictive methodologies. All of them dispatch the system by prioritizing the renewable sources, then the energy stored in the battery, and finally using the fuel-based generators as a backup source. In particular, LFS and CCS require no forecasting procedures and dispatch the system based on specific rules that take into account the State-Of-Charge (SOC) of the battery and the real-time mismatch between demand and production. In LFS and CCS, the fuel-based generator is usually kept uncommitted whereas the storage meets the difference between energy production and demand until batteries reach their minimum State-Of-Charge (SOC), thereafter the generator is turned on. In more detail, while LFS dispatches fuel-fired generators only to supply the load without recharging the battery, CCS allow conventional generators to recharge the batteries up to a fixed threshold and are shut down afterwards. These techniques require negligible computational requirements, thus they can be easily implemented in almost any control device or PLC. Conversely, in predictive strategies an optimization algorithm optimizes the scheduling of the system for the following hours, using the forecasting of both demand and renewable energy production for the following hours as an input. Therefore, when forecasts are accurate enough, the strategy accurately increases the coordination of components, leading to interesting savings in OPEX and NPC [6]. However, the optimization algorithm of predictive strategies is more complex than of LFS and CCS. Rolling-Horizon Strategies (RHS) are predictive approaches where the optimization is repeated even infra-daily, like every hour or less [7], [8], [9], [4]. Despite being deterministic approaches, they have proven to address uncertainties thanks to the fast re-scheduling procedure.

Likewise the optimal operation, another important task in mini-grid projects is minimizing the costs for the optimal design, while providing the adequate quality of electricity service. The majority of methodologies achieve the optimal design by means of programming techniques, like mixed-integer linear programming (MILP) [10], [11], [12], or heuristic approaches that, like in this paper, iteratively draw different size scenarios of the mini-grid and simulate the corresponding real-time operation of the system to evaluate an economic objective function [13], [10], [14], [15], [16], [17], [4], [18]. The quality of the service is usually evaluated as the ratio of the energy-not-served with respect to the total demand, and it is often penalized [4]. The methodologies rely on the forecasts of the behavior of the system by means of robust techniques [19], as well as of the specific renewable energy production for unit of assets, but there is no standard in assessing the demand of newly electrified mini-grids yet.

Estimating the energy and the shape of the load and the renewable energy production is required to identify the operating costs of the system, the topology of the grid being already defined. In heuristic approaches, the algorithm iteratively draws a new design of each component of the mini-grid, whose real-time operation is then simulated for an adequate time-horizon (usually a year) that characterizes the mini-grid behavior. As the design is fixed, the investment costs are known and the operating costs can be estimated, as well as the objective function, i.e. the Net Present Cost (NPC). LFS, CCS, and RHS are the main operating strategies simulated into heuristic approaches. If the complexity of the model fits the requirements, methodologies based on programming techniques can minimize the same objective function of heuristic approaches, but computational requirements can sharply increase, as the time horizon or the complexity of the model increase. However, they usually optimize not only the design of the system but also the operation in every time-step of the simulation. Authors in [20] highlighted interesting savings in the annualized costs of design methodologies with predictive approaches with respect to LFS and CCS operating strategies. The study in [4] and [7] highlighted similar results by minimizing the net present cost of the system. In particular, design approaches combined to predictive operating strategies have higher computational requirements with respect to LFS and CCS. Furthermore, authors in [4] revealed that the optimal design with RHS of the photovoltaic plant, the converters, and the battery storage is very close to the one with LFS, conversely to the one of the fuel-fired generators and the fuel tank.

In the present paper we propose a methodology to reduce the computational requirements of heuristic sizing techniques based on predictive approaches, especially focusing on the rolling-horizon. In particular, the procedure first heuristically optimizes the design of the mini-grid being operated with LFS, then the results are used to reduce the computational requirements of the subsequent fine-tuning optimization with RHS. Results are then compared with a standard techniques based on LFS and RHS. A case study is proposed using consumption data collected from a real mini-grid located in Kenya.

Section II describes the proposed procedure to reduce the computational requirements of sizing methodologies based on predictive techniques. Section III details the optimization model, which is the base component of the procedure; Section IV introduces the case study and Section V reports the results compared to standard techniques.

II. TWO-STAGE OPTIMAL DESIGN

As noted in [4], optimization methods involving advanced operating techniques like RHS require a considerable amount of resources and time; however, the optimal design of some components do not significantly differ from results achieved by the same optimizing technique with a simpler operating strategy like LFS. In the present study, we propose the two-stage procedure depicted in Fig. 1, to reduce the computational requirements of methodologies using RHS preserving the value of the objective function.

As in any heuristic optimizing technique, the proposed procedure requires the initialization of the area in which the solution is searched, the cost parameters, and the forecasts of the load and the renewable energy sources. Thereafter, a first optimization is developed (using LFS as operating strategy), whose corresponding optimal design is collected and used to refine the search area of the following RHS procedure, according to the following rules:

- The search area of components (PV, converters, and battery storage) whose optimal design do not significantly change with the operating strategy according to [4], is set within a range ($\pm 10\%$) of the solution achieved with LFS.
- For the other components, only the maximum capacity is modified as a multiplier of the design achieved with LFS (1.1 for fuel-fired generators and 2 for the fuel tank).

In this study, we introduce two simplified approaches for RHS:

1) RHS-upd: this method optimizes the system using the heuristic approach combined with RHS, modifying only search area. Since the search area is smaller, convergence speed is expected to be higher.
2) RHS-smp: in this case, the design of components, whose optimal capacity do not significantly change with the operating strategy according to [4], is set to the value obtained with the optimization using LFS. For the other components, the modified search area is used. In this case, not only the search area is smaller, but the number of variables to optimize reduces, thus convergence speed should be even higher than in RHS-upd.

III. STANDARD OPTIMIZATION METHOD

A. Heuristic optimization

The core of the two-stage optimization mentioned in the previous section is a standard heuristic optimization described

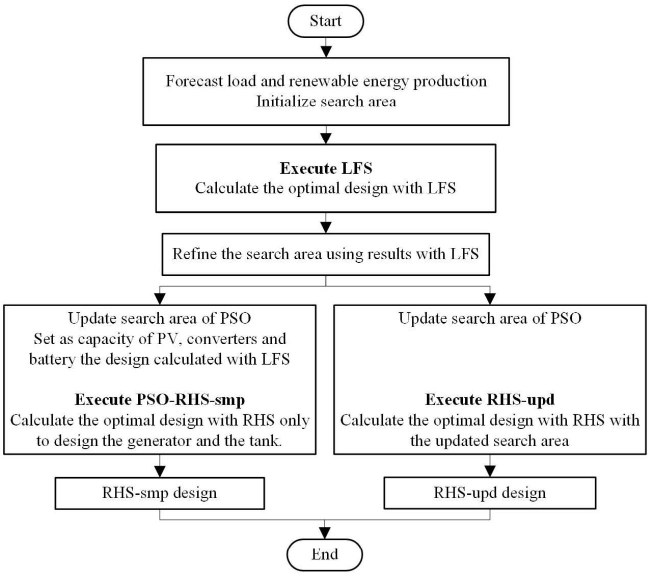

Fig. 1. Algorithm of the proposed two-stage optimization.

in this section. The methodology is based on a Particle Swarm Optimization (PSO) method [4] that minimizes the NPC of the system accounting for both investment costs and operating costs, including the economic value of the energy-not-served. The PSO procedure iteratively draws possible size scenarios for the components of the mini-grid within a preset search area; then the real-time operation of the system is simulated according to the operating strategy (LFS or RHS), which allows estimating the OPEX, based on the forecasts of the load and renewable energy production. Subsequently, the methodology calculates the NPC of the system and, when the termination criteria are reached, the procedure stops and the optimal size of the components is identified.

B. Operating strategies

1) LFS: The Load-Following Strategy is a priority-list method that prioritizes the use of the renewable energy, then the storage system, and finally the fuel generator, as a backup source. The generator is kept off-line until batteries reach the minimum energy level, thereafter the generator supplies energy the load, without recharging the battery.

2) RHS: The rolling-horizon approach is a predictive method that infra-daily redispatches the system to cope with uncertainties of the forecasts, as described in [4]. A MILP procedure re-dispatches the system every 6 hours, using updated forecasts; then a real-time dispatching method based on priority-list rules corrects the previous dispatch due to intrinsic forecasting errors. By advancing the behavior of the system, the proposed approach can be cheaper than traditional strategies, like LFS, as shown in [4].

IV. CASE STUDY

A. Description

The simplified approaches RHS-upd and RHS-smp, described in Section II, were compared to the standard approaches (LFS and RHS) detailed in [4] for a mini-grid in the Wajir County, Kenya. Due to the equatorial position of the site, the methodology was applied to a typical mini-grid composed by a photovoltaic system, a battery storage, an inverter, the battery converter, a diesel-fired generator and its fuel tank.

B. Load and renewable energy production

Both RHS and LFS require the forecast of the demand and the renewable energy production for at least a full year, hence we used real consumption data collected in a real mini-grid in 2014. Then, we simulated the stochastic nature of the load by adding a Gaussian error with standard deviation of 20% the actual demand.

The methodology to estimate the renewable energy production by the irradiance is based on the Graham method [21] and the HDKR technique [22], calibrated using data from a close meteorological station in Kitale, Kenya.

RHS is a predictive strategy that needs also short-term forecasts to anticipate the behavior of the system in every time step in which the scheduling procedure is performed. In the present paper, we considered an estimator having Gaussian forecasting errors with nil average value and a standard deviation that increases from 5% to 15% of the expected load, as the distance from the real-time increases to the 24^{th} hour.

C. Cost parameters and efficiencies

The cost parameters of the system were calibrated according to [4]. We considered economies of scale for the investment costs of converters and the fuel-fired generators, using equation (1), where x is the component, P_x the corresponding nominal capacity, $C_{0,x}$ is the cost of the component whose size is P_0, and the parameter β_x models the economies of scale.

$$C\left(x\right) = C_{0,x}\left(\frac{P_x}{P_0}\right)^{\beta_x} \tag{1}$$

A 1-kW diesel generator was assumed to cost 1k$, and the specific costs decrease by 13% as the capacity double, due to economies of scale modeled in (1). Similarly, a 1-kWp inverter was assumed to cost 1.9k$, and the specific costs decrease by 30% as the capacity doubles. The battery charger was modeled to be 33% cheaper than an inverter having the same capacity. Moreover, the cost of a 1000-l fuel tank was 680$ with a discounting factor of 32% as capacity doubles. Conversely, constant specific costs of 800$/kWp and 350$/kWh were assumed for the photovoltaic plant and the batteries, respectively, whose corresponding maintenance costs are 16$/kWp/y and 3$/kWh/y. The maintenance fee for converters is 3$/kW/y, while the operating costs for the generator is the sum of the fuel expense, valued at 0.9$/l, and 5c$/kW/h for each operating hour. The efficiencies of components were 96% for the battery (roundtrip), 96% for the inverter, and 99% for the DC-DC

TABLE I

Optimal design of the mini-grid with different heuristic optimization methods (LFS, RHS, RHS-smp, and RHS-upd).

Strategy	Exec. time (min)	NPC (k$)	CAPEX (k$)	Load curt. (%)	Diesel Prod (%)	PV (kWp)	Battery (kWh)	DC/DC Conv. (kW)	Inverter (kW)	Generator (kW)	Tank (l)
LFS	1.5	1871	1467	0.92	5.65	787	2122	401	227	95	3972
RHS	963	1838	1391	0.39	8.23	766	2016	391	207	38	4153
RHS-upd	506	1840	1393	0.35	8.25	762	2026	397	211	39	5568
RHS-smp	154	1844	1446	0.27	6.62	787[1]	2122[1]	401[1]	227[1]	36	4768

[1] Equals the optimal design using LFS

TABLE II

Simulations of the mini-grid designed with an operating strategy, LFS or RHS, and operated with the other.

Case	Operating strategy	Design obtained in	NPC (k$)	CAPEX (k$)	Load curt. (%)	Diesel Prod (%)
RHS(LFS)	RHS	LFS of Table I	1869	1467	0.14	6.84
LFS(RHS)	LFS	RHS of Table I	1902	1391	4.74	3.63

converter. The maximum efficiency of the fuel-based generator was 33% and its minimum working point 10%.

The specific cost of the energy-not-served was 1$/kWh for the high priority demand (the 20% of the total) and 0.5$/kWh otherwise.

D. Fuel procurement

When the level of the fuel tank reaches 20% of maximum capacity, a new fuel procurement is requested. Since the transport can delay, the refilling occurs hours or days later; the distance is modeled according to a probability density function, so that no refilling occurs before 2 days and the 90^{th} percentile of the distribution is 7 days. Every transport refills the tank by 80% of its capacity.

E. PSO parameters

The optimal size of each component is initially searched in a range between zero and a maximum capacity that is proportional to the peak demand (daily demand for storages) with a factor spanning between 2 and 10 depending on the component, so to be confident that the search area contains the optimal solution. This hypothesis is checked after the convergence of the PSO.

The tolerance was 0.1% and the number of stall iterations was 15. The number of particles simulated in each iteration was a constant multiple (10) of the number of variables, i.e. 20 particles for RHS-smp and 60 for all the other cases.

V. Results and discussion

Table I and Table II report the main results of the different heuristic optimization procedures; Table I details the optimal design of the system using the methodologies RHS-upd and RHS-smp detailed in Fig. 1. Whatever the operating strategy and the optimization technique, the mini-grid heavily rely on renewable sources and the diesel production is limited to no more than about 8% of the total load, although the cost of curtailing the low-priority demand was only 0.5$/kWh. The optimal design of the photovoltaic plant, the battery storage and the converters is very similar among the cases, which confirms the results achieved in [4] for a similar test. Conversely, the optimal design of the diesel generator and the tank is strongly related to the operating strategy, since the capacity of the generator is more than halved with RHS and the size of the tank increases. The optimal design of RHS and RHS-upd is practically equivalent, with the only exception of the design of the tank, due to the flatness of the objective function also considering that the CAPEX of the tank is about 0.1% of the NPC. These outcomes are consistent with the similar simulations performed in [4], thus the robustness of the approach is confirmed.

LFS case is the most expensive among all the other cases of Table I. In fact, RHS increases the coordination of components, which enables lower NPC, due to a strong reduction of CAPEX, partially counteracted by an increase in OPEX in cases RHS and RHS-udp since the energy produced by the fuel generator increases. In particular, the energy-not-served (ENS) with RHS strongly decreases by 60-80% with respect to LFS, but the diesel production increases from about 6% up to 7-9%, depending on the case. It is worth noticing that NPC of cases RHS, RHS-upd and RHS-smp is very similar; even more, the difference between RHS and RHS-udp is within the tolerance (0.1%) of the PSO algorithm, hence negligible.

The optimal design of the generator and of the tank of RHS-smp is very close to the results achieved with other RHS approaches, although the design of the other components was set to the value achieved with LFS. However, RHS-smp has much lower computational requirements, which are over 6 and 3 times lower than RHS and RHS-upd, respectively. This suggests that RHS-smp is an interesting approach to simplify the design of systems operated with advanced operating techniques.

In Table II, we detailed the simulations of the mini-grid system designed with LFS and RHS, as in Table I, but operated with other operating strategy, RHS and LFS respectively. In case RHS(LFS), which is the simulation of the mini-grid designed with LFS but operated with RHS, the NPC (1869$) is lower than the one (1871$) with LFS, detailed in Table I, but it is higher than the one (1838$) with RHS. This confirms that performing an integrated design including advanced operating techniques enables achieving a better design rather than using the advanced operating technique on a system tailored with LFS, since the sizing technique takes advantage of the increased coordination of components. On the other hand, in LFS(RHS), which corresponds to simulate LFS on a the mini-grid designed with RHS, the NPC (1902$) is higher than both RHS and LFS cases of Table I, since the diesel generator is undersized, which causes higher ENS.

VI. CONCLUSIONS

This study presents two sizing approaches to reduce the computational requirements of optimizing off-grid mini-grids operated with advanced predictive strategies. The proposed two-stage procedure first calculates the preliminary design of the system using a priority-list-based operating strategy, namely LFS, which converges very fast; subsequently, in the second stage, the optimization algorithm, tuned with the results obtained in the first stage with two different approaches, RHS-upd and RHS-smp, re-optimizes the system using the predictive strategy, that is RHS in the case study. The case study is calibrated with real data of a rural mini-grid in Kenya, composed by a photovoltaic plant, a battery storage, converters, a fuel generator and a fuel tank.

The net present cost calculated with the proposed approaches, RHS-upd and RHS-smp, practically equals the results with the standard RHS, with errors within 0.3% at worst. However, the computational requirements of RHS-upd and RHS-smp are more than 3 and 6 times lower than RHS. All the values are also lower than LFS, thus confirming the benefits of using predictive operating strategies.

The design achieved with RHS-upd is practically equivalent to RHS, with the only exception of the fuel tank, whose impact in terms of NPC is very limited ($< 0.1\%$). In RHS-smp the optimal design of the generator and the fuel tank is very similar to the previous results, although the other components were sized with LFS.

Therefore, this study succeeded in significantly reducing the computational requirements without seriously affecting the optimality of results and can provide a framework for researchers and practitioners in the field, especially in - but not limited to - rural areas of developing countries, where risks and costs are a serious concern.

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