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Generation and Network Planning of Utility-Scale Grid-Connected Microgrids

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An increasing acceptance of microgrid systems is primarily driven by emission reduction, resilience, reliability, and stability of energy systems. This work proposes a utility-scale grid-connected microgrid generation and network planning for a distribution network based on its available local resources and potential for distributed energy resource (DER) generator installation. Enabling distribution utilities to operate as a microgrid allows their systems to function as stand-alone in worst-case transmission grid scenarios. The main steps include identifying planning objectives, generation planning, and network planning. Results of a case study in Kalinga, Philippines show that the distribution utility can lower the levelized cost of electricity (LCOE) by 0.032 USD/kWh (21.38 %) by adding additional renewable energy capacities into the mix to meet its load demand. Results also show resilience and stability improvements with microgrid operation. Additional requirements for the existing distribution network to operate as a microgrid include additional network switches and line reinforcement upgrades.

1. Introduction

As sustainable development gains momentum globally, deployment of distributed energy resources (DERs) continues to emerge, especially with the customer-driven decreasing costs of renewable energy components. An essential aspect of this trend is the integration of various DERs into a microgrid system that consist of generation and storage situated near the center of demand (Farrelly and Tawfik, 2020). While the motivations for the increasing acceptance of microgrids vary - from reducing emissions (IRENA, 2021) and creating resilient, reliable, and stable energy systems (Basak et al., 2012) to integrating locally available energy supply into the grid (Konidena et al., 2020) – they share the common objective of meeting the increasing local demand.

No microgrid system is entirely the same due to the fact that they depend on network size, technology, local demand, resource availability, social context, and services they want to provide. As such, developing a standardized approach to microgrid planning remains a challenging task. Some papers explored generation planning for microgrids to optimize generator size (Nurunnabi et al., 2019), resource allocation (Barik and Das, 2021), and capacity mix (Khan et al., 2017). In contrast, other studies focused on network planning in terms of resilience (Mojtahedzadeh et al., 2021), reliability (Arefifar and Mohamed, 2014), and stability (Majumder, 2013). However, none have incorporated both into one unified framework.

In response to this research gap, this work proposes a novel and comprehensive microgrid planning methodology that seamlessly integrates both generation and network considerations. This methodology is centered around load prioritization, specifically within the context of a local distribution utility. Defined as a distribution utility with embedded generation, a utility-scale grid-connected microgrid is designed with the capability to work as a stand-alone microgrid should it get disconnected from the main grid (Ortenero, 2022). By empowering distribution utilities to maximize local resources in meeting their demand, an uninterrupted power supply can be ensured even without a main grid connection. Consequently, the study aims to improve the resilience of grid-connected distribution utilities, particularly those managed by electric cooperatives. By

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enabling their systems to operate autonomously in worst-case main grid scenarios, this research contributes to bolstering energy security.

2. Methodology

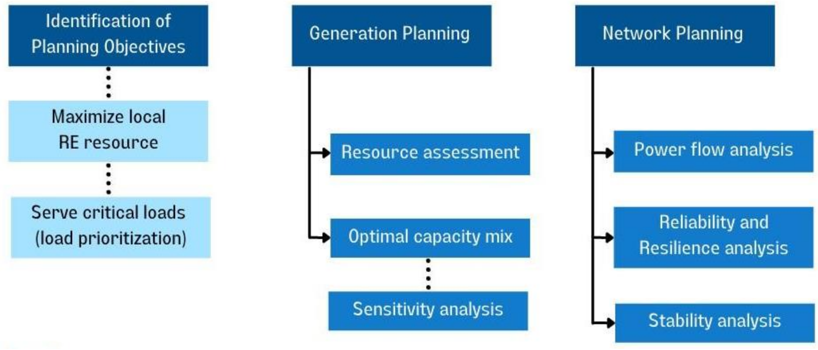

Figure 1: Overall methodology for the proposed planning framework for utility-scale grid-connected microgrids.

2.1 Identification of planning objectives

Figure 1 summarizes the proposed microgrid planning framework. An essential preliminary step in the planning process of distribution utilities is to identify the planning objectives. These objectives motivate the planning measures that the utility operators are about to develop. In this work, the microgrid planning objectives are mainly to maximize local distributed energy resources (DER) and maintain the supply of critical loads, especially during contingencies. The capacities of the resulting available DERs were optimized for the energization of the whole utility-scale microgrid at varying load levels.

2.2 Generation planning

The renewable energy resource assessment is conducted using geospatial data. Considering constraints such as ancestral domain and protected areas, tree covers, and main roads, the site-suitability of the potential of specific energy resources was obtained. The first step is to identify the potential solar power plant farm capacity and sites. Due to technical limitations, this work adopted the recommended representative days of each month using Julian day and incidence angle declination (Duffie and Beckman, 2013), reducing the number of simulations from 365 to 12 runs. The solar noon data were identified using the methods of the NOAA Global Monitoring Division. After classifying the clear-sky GHI raster based on the constraint criteria, suitable sites for solar farms are obtained, including their theoretical extractable solar energy.

To identify theoretical wind farm locations, digital elevation models (DEMs) were used as the primary source of data. The constraint criteria for the wind resource are similar to that of the solar resource, with the addition of main roads. In determining the location of coordinates, wind data were obtained from (NREL, 2017), measured at a 60-meter elevation. To match the hub height of the wind turbine and existing wind farms with similar topographic characteristics, the Katabatic power equation is used. The wind shear exponent used depends on the surface roughness of the area (Khalfka, 2018). Calculation of the power generation of the wind turbine is determined using the total available wind power at the measured wind speed as well as considering the wind speed distribution based on Weibull probability distribution (Shi, 2021). To estimate the theoretical wind energy production, the average wind turbine periodic energy production is calculated and multiplied by the number of wind turbines assumed to fill a specified location. A rule of thumb is that the wind turbine spacing equals seven times the rotor diameter (Gaughan, 2018).

The final step in the resource assessment is to show how the outflow points of the hydro resources are identified. Using the DEMs, the river networks and catchment basins are identified through the SAGA function in QGIS. The outflow points of the watersheds are determined using the flow direction, Strahler order, and contour. Based on the same constraint criteria, the outflow points that fall under these areas are disregarded. The mathematical model for the flow rate is estimated in terms of precipitation and temperature using multiple linear regression (Kostic et al., 2016).

As part of DER planning, it is crucial to identify design constraints and requirements as well as technical and economic modeling. Therefore, this work looked into the optimal hybrid system architecture in terms of levelized cost of energy (LCOE) using the distribution utility load profile, resource data obtained from the resource assessment, and techno-economic assumptions available from the literature (Ocon and Bertheau, 2019). Using the said data, HOMER Pro® is used to calculate additional power (renewable or conventional) generator capacities and energy storage system capacities for the distribution utility. This is done by finding the least-cost energy mix to obtain optimal sizes with constraints imposed on the cases and scenarios.

2.3 Network planning

Corresponding network upgrades need to be identified to maximize the benefits of DG integration and microgrid operation. One network upgrade considered was the installation of new switches whose goal was to allow the formation of microgrid islands supplied by DGs when a local interruption occurs while prioritizing the continuous energization of critical loads. The data used here are the potential locations of new DERs identified in the resource assessment and the resulting optimal capacities of dispatchable DGs. The new switches were allocated through optimization based on a Greedy Randomized Adaptive Search Procedure (GRASP) method (Lopez et al, 2016).

The power flow analysis was performed using OpenDSS. The available data was converted to objects understood by the simulation software. Power flow analysis was then performed to run for 24 h. Then based on power flow analysis results, network components were upgraded to ensure that pertinent issues such as line overloading, transformer overloading, and undervoltage loads were resolved before converting the network into a microgrid.

For the reliability analysis, sequential Monte Carlo (MC) methodology was used to evaluate the reliability increase from a microgrid planning investment. The reliability levels of two network configurations were evaluated: (1) base and (2) microgrid-enabled. The methodology used in resilience analysis is the non-sequential MC simulation which evaluates the resilience of a network by subjecting it to several extreme-event scenarios. The non-sequential MC methodology employed three steps: (1) extreme event modeling, (2) damage assessment and system response, and (3) calculation of the resilience metrics (Gautam et al., 2021). The same configurations from the reliability analysis were considered in the resilience analysis. The resilience metrics used to assess the level of resilience of the network focus on the ability of the system to maintain the supply of power to the critical facilities; critical facilities are loads from sectors that are crucial in the functioning of the community, especially during emergencies. The standard reliability indices, such as system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), expected energy not supplied (EENS), etc., were modified to count interruptions experienced by loads grouped depending on criticality.

When enabling microgrid operations on a distribution network, we must consider frequency stability. There must be a sufficient power generator for any power system to supply the demand while maintaining power supply quality through stable frequency and voltage. This study on microgrid stability focused on the capabilities of the microgrid during grid disconnection events. The local generation should gracefully transition in-between modes while meeting power quality constraints during the grid-connected mode.

3. Case study for Kalinga, Philippines

3.1 KAELCO system

Kalinga-Apayao Electric Cooperative, Inc. (KAELCO) is a grid-connected distribution utility in the northern Philippines that provides electricity to Kalinga and some municipalities of Apayao. The Philippine Department of Energy designated some parts of the Kalinga-Apayao area as a “competitive renewable energy zone”, including the potential for developing run-of-river power plants owing to the area’s mountainous terrain and vast river network. However, the available regions for installing renewable energy generators are limited since most places within KAELCO are protected areas and ancestral lands, aside from the mountainous terrain. Such exploration and development constraints must be considered. Unfortunately, the obtained data regarding the distribution network (e.g., feeder and outage data) had insufficient range and lacked some attributes, such as protective devices, so appropriate assumptions were made.

The critical loads connected to the KAELCO distribution system were identified based on the Critical Facility Areas classification in the exposure database developed (Jakab et al, 2014). Only a small fraction of the load peak demand corresponds to critical loads, which is expected as most of the customers of KAELCO are residential customers. Three (3) case studies have been generated based on the identified total and critical load demands: Case 1. The energy system configuration that will be generated supplies the total KAELCO load; Case 2. The energy system configuration that will be generated supplies all critical loads; and Case 3. The energy system configuration that will be generated supplies highly critical emergency life-supporting loads only. Scenarios are generated based on possible energy system configuration, which covers all three (3) cases with the following descriptions: Scenario 1. KAELCO load demand is being supplied by the one-megawatt mini hydroelectric plant and the main grid (base scenario); Scenario 2. KAELCO is connected to the grid, but excess supply generated by the existing and proposed (based on calculations) power generators can be sold back to the main grid.

3.2 Results and Discussion

From the solar resource assessment, Tabuk City and the Municipality of Rizal, both located in Kalinga, are the most suitable sites for solar PV installations, with a usable space of 3,529.36 km². The total available area is translatable to 3,803.63 GW of extractable solar power based on the 1,077.71 W/m² average peak power of the usable area. Results from the wind resource assessment identified five potential locations for wind farm installations after taking into account the ancestral domain and protected areas, and main roads. There are 936 wind turbines with a rotor diameter of 120 m that can be installed within the KAELCO franchise area. This is translatable to the total periodic energy production of 9,937.25 GWh, enough to cover the KAELCO load demand. For the hydro resource assessment, four sites were found suitable.

This work only considered hybrid system configurations having the lowest generated LCOE. Even though lithium-ion batteries and flywheels were initially considered for energy storage in the analysis, the optimal system architecture only considered the flywheel in the capacity mix. A report on microgrids with energy storage (Clamp, 2020) details the benefits of using flywheel as the energy storage system. While the computed LCOE for Scenario 2 ranges from 0.113 USD/kWh to 0.116 USD/kWh, these figures are relatively lower than the LCOE of the base scenario at 0.145 USD/kWh; this indicates a 0.032 USD/kWh (21.38 %) reduction in LCOE. The lower LCOE can be attributed to the diversified capacity mix of Scenario 2 compared with Scenario 1. The abundance of renewable resources (solar, wind, and hydro) within the KAELCO franchise area allows the immediate application of the microgrid system to promote grid flexibility. For the optimal microgrid systems, hydro is the most utilized resource all year round, followed by wind at 7,442 h and solar at 4,335 h. On the other hand, the diesel generator for Scenario 2 Case 2 only operates at 16 h. The component operation hours could also explain why the hydro resource has the highest capacity in the optimal microgrid system, followed by wind, then solar. Figure 2 illustrates the resulting optimal capacity mix of additional DERs.

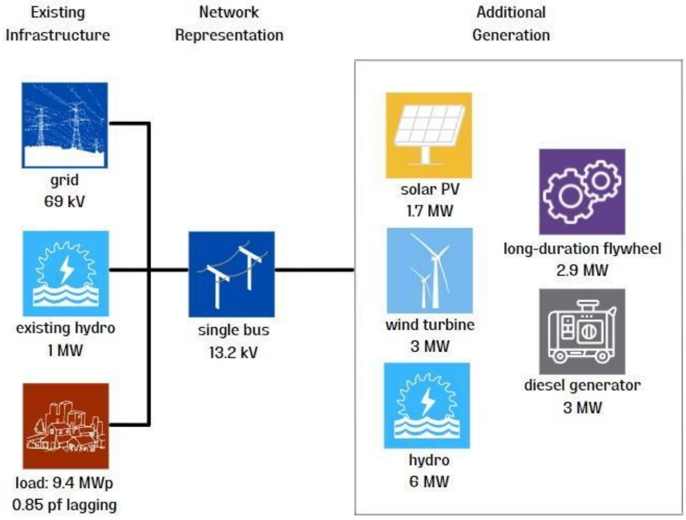

Figure 2: Single bus KAELCO network model with the resulting capacities from the optimal capacity mix

Adding new capacities to the distribution utility's current capacity mix also increases renewable energy penetration from 5.29 % to 39.4 % (for Scenario 2 Cases 3 and 4) and 45.7 % (for Scenario 2 Case 1). The new configurations also offset CO2 emissions from 25,364,376 (Scenario 1) down to 2,884,846 kg/yr (Scenario 2 Cases 3 and 4) and 1,086,954 kg/y (Scenario 2 Case 1).

The presence of distributed energy resources (DERs), sellback, and energy storage altered the calculation for the percent system loss. The results indicate that incorporating DERs leads to a higher percent system loss compared to the pre-DER scenario. However, the system loss remains stable throughout the day with DERs, unlike the base scenario without DERs. The inclusion of DERs also increased voltage levels across all distribution utility feeders. However, undervoltages still occur during periods of high demand.

The integration of GRASP optimization switches improved the reliability and resilience of the microgrid-enabled network. SAIFI decreased from 197.04 interruptions/y to 114.39 interruptions/y, indicating improved service reliability over the base scenario. The introduction of switches isolated network segments, forming islands with distributed energy resources (DERs) to mitigate fault impacts. SAIDI also exhibited a reduction, resulting in shorter interruption durations for loads in the same zone as the DERs. Although the improvement in SAIDI was modest (2.2412 h/y to 2.1830 h/y), it was attributed to the limited deployment of dispatchable DERs in the extensive distribution network.

Focusing on typhoon events as it is the most common in the region, the nonsequential Monte Carlo resilience assessment demonstrated the significant enhancement of the entire system's resilience and highly critical load resilience, as shown in Table 1. $SAIDI_{sys}^{Typhoon}$ and $EENS_{sys}^{Typhoon}$ metrics showcased considerable improvements. The improvement in $SAIFI_{sys}^{Typhoon}$ is subtler than those in the previous two metrics. The $SAIFI_{sys}^{Typhoon}$ can range from 0 (customers experience zero interruptions during typhoons) to n (all customers experience interruptions at least once during typhoons and may cascade up to n outages).

Table 1: Overall resilience against typhoons of the microgrid-enabled network versus the base scenario network

Network Configuration	$SAIFI_{sys}^{Typhoon}$	$SAIDI_{sys}^{Typhoon}$	$EENS_{sys}^{Typhoon}$
Base Scenario	1.0000 customer- interruption/event	22.5362 h/event	30.1048 MWHr
Microgrid-enabled	0.9580 customer-interruption/event	13.2465 h/event	19.1168 MWHr

Table 2: Stability test scenarios made by changing variable generation and demand

Test Scenario	Irradiance (W/m2)	Wind Turbines	Real Power Demand	Pre-islanding Grid State
1	1000	2	9.4 MW	1.70 MW exported to grid
2	1000	4	9.4 MW	4.70 MW exported to grid
3	250	2	9.4 MW	0.13 MW imported from grid
4	0	0	9.4 MW	1.10 MW imported from grid

Using Matlab/Simulink, the stability analysis was conducted for the hypothetical microgrid-enabled system. The system was modeled using Matlab-validated power system blocks, with parameters adjusted based on plant size and resource assessment. Test scenarios prior to microgrid islanding were outlined in Table 2. Simulation results revealed that without microgrid-specific protection or islanding-enabled control systems, frequency instability could occur when there is significant net power export or import from the grid. The risk of instability during the transition period increased with larger deficits or excesses in microgrid supply, especially when variable generation exceeded capacity, leading to overfrequency. However, there are potential solutions to improve microgrid stability, such as implementing frequency-relay-based protection to curtail excess generation during high power export before islanding. Proper relay settings, including the use of frequency relays to disconnect DER generation like solar or wind power, helped mitigate resulting over-frequency.

4. Conclusion

This work presents a utility-scale grid-connected microgrid generation and network planning methodology. Both resource availability and network capability are examined to determine the potential for microgrids and islanding disconnection upgrades. Based on the case study in Kalinga, Philippines, the local resources such as solar, wind, and hydro available within the KAELCO franchise area is more than enough to meet local demand. The resulting microgrid system configuration provides a lower LCOE than when the distribution utility continues with its base scenario. The network was determined to have the potential to operate as a microgrid after upgrades to network switches and protection devices, demonstrating improvements in power flow, reliability, resilience, and stability. Overall, outcomes from the combined generation and network planning framework can help distribution utilities achieve less expensive and sufficient power supply and provide more robust network operation, which is advantageous for end users, especially for facilities with highly critical functions. Future work can direct more focus on gathering comprehensive data, both for generation and network planning, to ensure all factors are considered. Additionally, other renewable resources and energy storage technologies can be examined for resource assessment, while resilience analysis can also include other types of natural and man-made hazards.

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