IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 11, Issue 6 Ver. I (Nov. – Dec. 2016), PP 29-40
www.iosrjournals.org

Enhancing Resilience of Electric Power Service in Developing Countries through Micro grid

Kwa-Sur Tam
Department of Electrical & Computer Engineering, Virginia Tech, U.S.A.

Abstract: *Economic growth and competitiveness of developing countries are hampered by frequent and lengthy power outages. Although disruptions to a power system cannot be completely prevented, a power system can still function if it is designed to withstand and recover from disruptions. Resilience refers to the attribute of a power system that enables all or a portion of the electric loads to be served during an event that causes power outages or even blackout. Microgrid is one approach that can enhance resilience of electric power systems. The goal of this paper is demonstrate that microgrid can enhance the resilience and energy security of cities in developing countries. It shows how a microgrid may be used to improve the resilience of the electric power system serving Kigali against blackouts. A new measure of resilience is introduced to gauge the impact of microgrids on resilience enhancement. Features of microgrids that are especially pertinent for developing countries are presented.*

Keywords: *Microgrid, resilience, renewable energy, energy independence*

I. Introduction

On December 11, 2015, Kigali, the capital city of Rwanda, experienced a power blackout that lasted for more than 24 hours. Kigali businesses suffered from loss of revenue and perishable goods, idling of workers, damage to equipment during the power surge after outage, and the cost of on-site generation [1, 2]. In the summer of 2012, India experienced a blackout that lasted for two days and affected 600 million people. Indian business managers considered poor electricity supply as their biggest barrier to growth [3]. In developing countries individuals and businesses not only experience frequent power outages but also uncertain restoration schedules as well as unreliable power quality with fluctuating voltages and power [4].

Small and medium-sized enterprises (SMEs) are critical for the well-being and growth of the economy of developing countries just like they are in developed countries. In OECD (Organization for Economic Cooperation and Development) countries, SMEs and micro enterprises account for over 95% of all firms and 60-70% of employment [5]. In a developing country such as Rwanda, the SME sector accounts for 98% of the businesses and 41% of all private sector employment [6]. Surveys showed that power outages are considered a major obstacle by a majority of SMEs [7]. Unlike big enterprises, SMEs may not be able to afford the costs of on-site generators such as diesel generators. The losses associated with power outages or the costs of on-site generators increase their costs of doing business, render them less competitive and reduce the prospects of attracting new investments. With rapid globalization and liberalization of international trade, many manufacturing activities are getting shifted to developing countries where costs are lower. To grow the manufacturing sector for both domestic demand and export, it is essential to have reliable and resilient electric power service [8].

The impact of a blackout exponentially increases with the duration of the blackout, and the duration of restoration decreases exponentially with the availability of initial sources of power [9]. The ability of a power system to withstand disruptive events is referred to as its resiliency. A resilient system can provide at least a portion of its loads even when the disruptive event is still ongoing and can quickly recover after the event is over. In developed countries such as the United States, power systems are reliable but may not be resilient. For example, weather-based events such as hurricanes can disrupt power services to many customers for days. In developing countries, power systems may not be as reliable but they can be made more resilient.

Microgrid is one approach that can enhance the resilience of electric power systems. A microgrid is a cluster of loads, distributed generation (DG) units, energy storage systems (ESSs) that are operated in coordination under the command of a microgrid controller [10]. Rapidly advancing technologies have improved the options of technologies – from PV arrays to software controls – that make microgrids work. Microgrids help communities achieve local resilience for vital services and interdependent community assets to support public safety, convenience, and economic growth [11].

A lot of work has been published on the control and operation of microgrids to protect the critical loads inside the microgrids [10, 12 – 14]. However, the flexibility of a microgrid can also be utilized to improve the performance of the host system that is outside the microgrid. The goal of this paper is demonstrate that microgrid can enhance the resilience and energy security of cities in developing countries. It shows how a microgrid may be used to improve the resilience of the electric power system serving Kigali against blackouts such as the one that occurred on December 11, 2015. This topic is especially relevant for developing countries in which resilient power systems are important for economic development. This paper presents information on the technical and economic aspects that can be useful for all parties involved in making policy decision on sustainable development.

More than half of the world's population has been living in cities since 2007. This trend of urbanization will continue, especially in Africa and Asia [15]. Unlike cities in much of Asia and Latin America, urbanization in Africa seems to have decoupled from economic development [16]. Most African cities are growing without having significant foreign direct investment and do not serve as engines of growth for the economy. A reliable and resilient power supply can enable private enterprises – especially SMEs – to develop and turn this situation around. Urban energy planning will play a critical role in creating a sustainable energy future and microgrid should be included in the planning process. This paper contribute useful information that can be used in the planning process.

Section II introduces the important attributes of microgrids. Section III discusses resilience and introduces a new measure of resilience to measure the impact of microgrids. Section IV presents a case study using the situation in Kigali as demonstration. Section V discusses the implications for the formulation of policy and development strategies. Conclusions are presented in Section VI.

II. Microgrids

A micro grid is a cluster of power sources, an energy storage system, and loads that are operated in coordination autonomously to achieve a prescribed function. The prescribed function could be the integration of renewable energy as power sources, the improvement of power quality and reliability for certain mission-critical loads within the microgrid, the enhancement of resilience both inside and outside the microgrid (as shown in this paper), or a combination. The prescribed function may be further supported by controlling certain loads (the controllable loads) remotely to manage the response of the load demand.

Figure 1 shows the generic structure of a microgrid. A microgrid is connected to the host power system through a fast-acting switch at a single point of connection – the point of common coupling (PCC) – and the microgrid is perceived by the host system as a single entity. A microgrid may operate in the grid-connected mode when the switch at the PCC is closed or in the stand-alone mode when that switch is open. Upon detection of problems in the host system, the microgrid can quickly change from the grid-connected mode to the stand-alone mode so that the loads inside the microgrid are protected from the problems in the host system.

As shown in Fig. 1, the control architecture of a microgrid is hierarchical and consists of the primary control, the secondary control and the tertiary control [17]. The primary control is responsible for the local control of each component and provides the fastest response. The secondary control is responsible for the reliable and economic operation of the entire microgrid by coordinating the operation of individual components. The tertiary control coordinates the operation of a microgrid (or several microgrids) with the host system. The primary control receives commands from the secondary control which in turn receives commands from the tertiary control. The power sources may include diesel generators, microturbines, solar photovoltaics, fuel cells and other small-scale renewable energy sources. Some of these power sources may be used in the combined heat and power (CHP) mode to meet both the thermal energy requirement and the electric energy demand within the micro grid. Energy storage systems (ESSs) play an important role in microgrids. With ESS, power generated does not have to match the power demand instantaneously all the time but can be time shifted for more optimal operation. This aspect results in much flexibility in operation as well as economic benefits [18]. ESS can provide backup and increase reliability. ESS can enhance the quality of electric power provided to the loads within the microgrid.

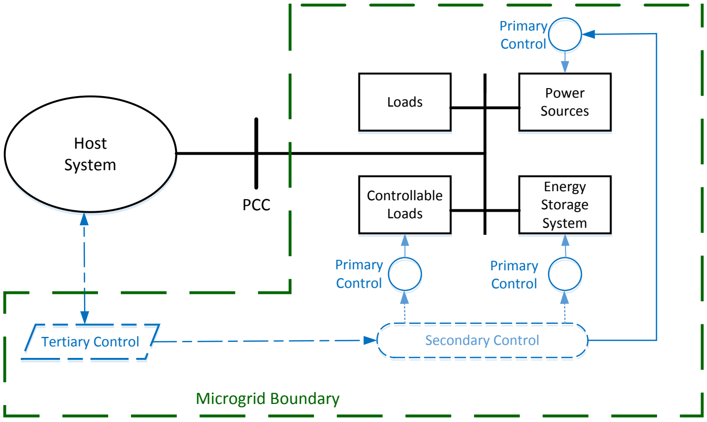

Fig. 1 Generic structure of a microgrid

Table I Energy storage technologies and some of their characteristics

Energy Storage Technology	Round-trip AC Energy Efficiency	Discharge Duration (hours)	Response time	Equipment Cost ($/kW)
Compressed Air (small)	0.6 – 0.7	3 – 5	seconds	1800 – 2100
Flywheel	0.84 – 0.86	0.03 – 1	milliseconds	1200 – 1600
Valve Regulated Lead Acid Battery	0.68 – 0.78	2 – 4	milliseconds	1600 – 2500
Advanced Lead Acid Battery	0.8 – 0.9	2 – 5	milliseconds	2200 – 3900
Lithium Ion (High Power) Battery	0.84 – 0.91	0.25 – 1	milliseconds	800 – 1200
Lithium Ion (High Energy) Battery	0.85 – 0.92	1 – 4	milliseconds	2500 – 3500
Sodium Sulfur Battery	0.73 – 0.80	6 – 7	milliseconds	2600 – 3100
Sodium Nickel Chloride Battery	0.82 – 0.87	2 – 4	milliseconds	2000 – 3000
Ni Battery (NiCd, NiZn, NiMH)	0.7 – 0.8	0.3 – 3	milliseconds	1100 – 1900
Vanadium Redox Battery	0.58 – 0.68	3 – 5	milliseconds	2200 – 3100
Advanced Vanadium Redox Battery	0.65 – 0.70	3 – 6	milliseconds	2000 – 2500
Zinc Bromide Battery	0.62 – 0.70	2 – 4	milliseconds	1200 – 3000
Zinc Air Battery	0.65 – 0.77	5 – 6	milliseconds	1200 – 1400
Supercapacitors	0.92 – 0.97	0.08 – 1.2	milliseconds	600 – 1000
Hybrid Lead Acid and Super-capacitor	0.82 – 0.87	0.5 – 5	milliseconds	1000 – 1200
Superconductive Magnetic Energy Storage	0.95 – 0.99	0.003 – 0.008	milliseconds	1000 – 6000

Table 1 shows the energy storage technologies applicable to microgrids and some of their characteristics. Functions performed by energy storage systems may be power-based or energy-based. The power-based functions are associated with the power ratings of the power electronic interfaces of the energy storage systems and they usually require short response times (milliseconds to seconds) and short discharge duration. An example of a power-based function is the smoothing of the power outputs from intermittent and variable renewable sources. The energy-based functions are associated with the amounts of energy that the energy storage systems can store and they usually require longer discharge durations (minutes to hours). An example of an energy-based function is the time-shifting of solar energy from the time that they are received from the sun to another time such as nighttime. An ESS can be designed and used to perform both power-based functions and energy-based functions.

The costs of energy storage have been decreasing due to advance in technology. Besides applications in microgrids, energy storage systems have been developed for electric transportation, community storage and residential applications. The economy of scale from large scale production to support the diverse applications also contributes to the decrease in costs of energy storage. The prospect that a single energy storage system can perform multiple functions further improves the economics of energy storage.

Fig. 1 shows that the components of a microgrid is contained inside a boundary. Although not a physical borderline, the boundary is well-defined to include all components that are controlled by the microgrid control hierarchy. This constitutes a major difference between a microgrid and the conventional distributed energy resources (DERs) which consist of distributed generators (DGs) and energy storage. While the conventional DERs or DGs are treated by the host system as separate entities individually, the entire microgrid is treated by the host system as a single entity at the PCC either as a load or a generator depending on what the host system wants the microgrid to do.

Through microgrids, high penetration of renewable energy can be integrated into the host system without introducing significant adverse effects due to the variability of renewable energy. When intermittent and variable renewable energy sources are used as the power sources, the microgrid control hierarchy command the ESS to smooth out the variation and firm up the intermittency so that dispatchable power can be either used internally inside the microgrid or export externally to the host system. None of the fluctuations of renewable energy are exported to the host system. Since the conventional DERs or DGs are treated by the host system as separate entities individually, the variability and intermittency of renewable energy-based DERs or DGs could introduce significant negative impact at high penetration levels.

There is another major difference between the microgrid and the conventional DGs. When a disruptive event (such as a fault or a cascading sequence of failures that lead to blackout) occurs in the host system, the microgrid detects this event and changes its operation from grid-connected mode to the stand-alone mode by opening the fast switch at the PCC so that the loads inside the microgrid will not be affected by the disruptive event or its aftermath. Due to safety and other concerns, the IEEE Standard 1547 requires that the conventional DGs be disconnected from the host system for a prescribed duration when a fault is detected [19]. Therefore, the conventional DGs cannot supply electric power to the loads when they need them the most.

Currently, there are two modes of electric power service in developing countries. Electric power can either be obtained from the utility power grid or from customer-owned generators, mostly diesel generators. Microgrids provide a third mode. Customers can group together to establish a community microgrid to share the power sources and the energy storage system. Depending on the economics, the microgrid can be connected to the utility power grid or be operated in the stand-alone mode. Businesses that require higher reliability or power quality can obtain a higher priority for the power generated within the microgrid by paying higher prices. Investors might be interested in building and operating microgrids when they see profitable business models. Microgrids can provide a catalyst in bringing more reliable and resilient electric power services to urban areas and electrification to rural areas.

Microgrids also provide an alternative to enhance reliability and resilience of electric power systems. Conventionally, the notion of redundancy has been the main approach for increasing reliability [20]. This approach is usually expensive because the building of transmission and distribution systems is costly. By locating the power generators and energy storage close to the loads, microgrids can enhance reliability and resilience not only for loads inside the microgrid but also the system outside the microgrid (to be demonstrated in Section IV). By properly designing and operating microgrids, the need to build costly redundancy into the system can be minimized.

III. Resilience

Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events [21]. This definition is applicable for various infrastructure sectors such as electric power systems, transportation systems, etc. The effectiveness of a resilient infrastructure depends on its ability to anticipate, absorb, adapt to, and rapidly recover from a disruptive event. Disruptions to a power system cannot be completely prevented but a power system can still function if it is designed to withstand and recover from disruptions. Resilience refers to the attribute of a power system that enables all or a portion of the electric loads to be served during an event that causes power outages or even blackout. A resilient power system not only can increase the well-being for all of its customers but also can increase the competitiveness of its industrial and commercial customers by providing shorter down-times. Resilience is a sought-after attribute in future power systems [22, 23].

Resilience is not the same as reliability. Reliability refers to a system's ability to consistently provide service in terms of quantity and quality. A system can be reliable but not resilient if it cannot recover from a disruption even though the frequency of disruption is small. Conversely, a system can be resilient but not reliable if it can always recover from the disruptions that happen quite often. While a microgrid can increase reliability as well as resilience, resilience enhancement is the focus of this paper.

Reliability is usually expressed in entities such as failure rate (λ), the mean time to failure (MTTF), the system average interruption frequency index (SAIFI), etc. These indices are usually computed by using statistical data collected over time. Developing countries such as Rwanda usually do not have much of these data yet. This paper proposes a measure of resilience that can be determined by using power flow analysis and contingency analysis. The tools for these analysis are commonly available for developing countries as well as developed countries. The new resilience metric, the event resilience index (ERI), as defined by (1), is especially useful to measure the impact of microgrid on enhancing the resilience of electric power service to an urban area.

$$\text{Event Resilience Index (ERI)} = \frac{\begin{array}{c}\text{Electric Loads Served Within The}\\ \text{Prescribed Area During The Event}\end{array}}{\begin{array}{c}\text{Electric Loads Served Within The}\\ \text{Prescribed Area Before The Event}\end{array}} \qquad (1)$$

Fig. 2 shows the percentages of load served before and during an event. If the pre-event load is taken as 100%, then ERI is equal to 1 if 100% of the load is served during the event (after a short transient period), 0.4 if 40% of the pre-event load is served during the event, and 0 if none of the pre-event load is served during the event. Compared to other measures of resilience that have been proposed from different viewpoints [24, 25], the ERI is especially useful for developing countries because its computation is not complicated but it provides useful information on what percentage of the load is expected to survive during the event.

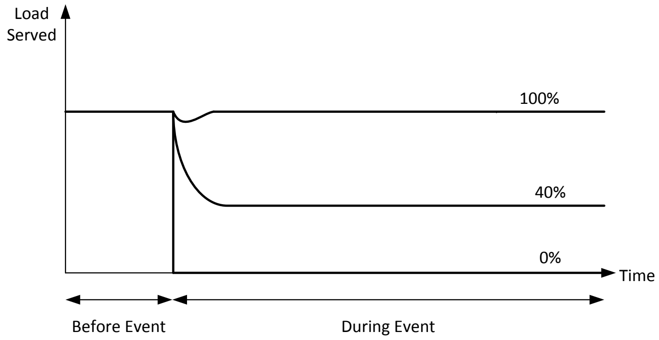

Fig. 2 Percentages of pre-event load served during an event

ERI is defined for an area within prescribed boundary. For example, in Section IV, the Airport Area ERI (AA-ERI) is defined for the area that includes the Kigali International Airport and the Kigali City ERI (KC-ERI) is defined for the rest of Kigali sans the airport area. Since the microgrid also has well-defined boundary, ERI is especially useful in describing the impact of microgrid on resilience enhancement for the same area.

IV. Case Study

The transmission grid of Rwanda is shown in Fig. 3. The backbone consists of two 110-kV lines that join at Kigali. A 70-kV line connects Kigali to the electric loads on the eastern portion of the country. Separate 30-kV systems are connected to the 110-kV lines and the 70-kV line at different locations of the country. The topology of the overall transmission system is quite radial with only minor networking taking place at the sub-30 kV voltage levels.

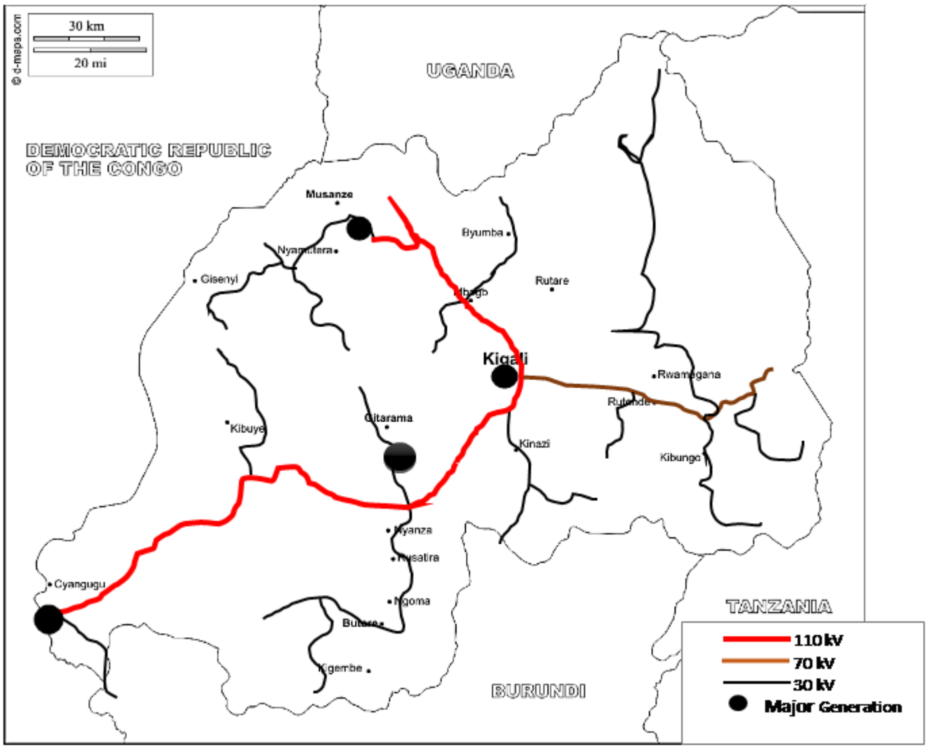

Fig. 3 Transmission System of Rwanda

Kigali is located near the center of the country. The electric loads in Kigali are served by the power transmitted through the two 110-kV lines and from local generation. The northern line transfers power from the hydroelectric power plants from the northern region. The southern line transmits power generated in the south and the western parts of the country. Losing either one of the 110-kV lines can cause blackout in Kigali. The blackout that happened on December 11, 2015, was caused by outage at the southern line. Due to the lack of generation and the radial nature of the transmission system, power outages happen often in Kigali and are usually lengthy.

Rwanda is vulnerable in its electric supply because of the following reasons. Firstly, the hydropower reservoirs that Rwanda currently depends on for most of its electric power supply were vulnerable to prolonged drought such as that between 2003 and 2005. Secondly, Rwanda is a landlocked country and currently about one third of its electricity is generated from diesel and heavy fuel oil imported through neighboring countries. The energy security of this country is vulnerable not only to fluctuations of fuel prices but also its relationships with the neighboring countries as well as the political stability of these countries.

The high cost of diesel fuels for backup generators used in power outages increases the costs of doing business. For long term sustainability, it is critical to develop locally available renewable energy resources besides hydropower. The use of renewable energy can reduce pollution and the dependence of fossil fuels. For a landlocked country like Rwanda that depends on imported fossil fuels, the use of renewable energy can enhance electricity security by minimizing its dependence on imported fuels and the neighboring countries for the transportation of imported fuels.

Frequent power outages have negative impact on businesses, especially for small and medium-sized enterprises (SMEs) that may not have the resources to operate their own generators for backup. When the electric service is restored, the associated voltage spikes could impose damages to unprotected electrical equipment, causing further outages and cost increase [26]. Companies that can afford to install diesel generators for backup have to include high fuel costs into their costs of doing business. The country is looking for ways to improve the electric power services to attract more business and foreign investment. This paper proposes that microgrid can provide the solution to this problem.

Based on the existing pattern of power generators, electric loads and their interconnection within Kigali, three areas have been identified as candidate areas for the development of microgrids. These microgrids are referred to as the Airport Microgrid (Airport MG) for the area that includes the Kigali International Airport, the Kigali Center Microgrid (Kigali Center MG) for the area that includes the control center, and microgrid 3 (MG3) for the third candidate area. These candidate microgrids and their respective points of common coupling (PCCs) are shown in Fig. 4.

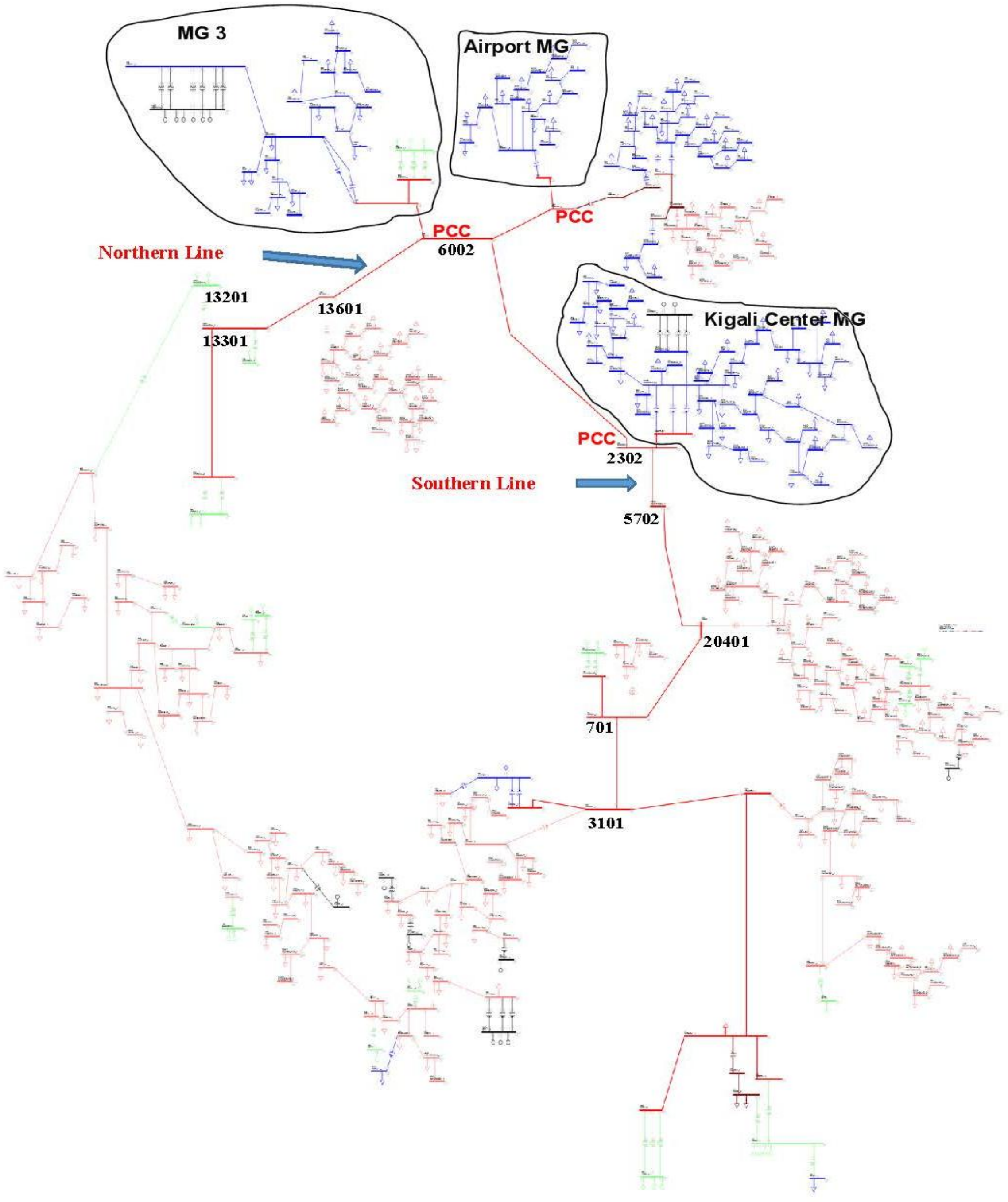

Fig. 4 Prospective sites of microgrid in Kigali

MG3 has more generation than load. If MG3 is operated in the stand-alone mode, the host system will lose access to the surplus generation of MG3 when those generation resources are needed the most. For this reason, MG3 should be connected to the host system at all time and is not a good choice for the development of microgrid.

Between the Airport MG and the Kigali Center MG, the former is chosen because the Airport MG includes the Kigali International Airport. Since Rwanda is a landlocked country, its airport is important, especially during a disaster or a national emergency. The airport is also important for tourism which is important for the economy of Rwanda.

The airport area has no generation of its own. The daily load profile for the airport area is shown in Fig. 5 [27]. Since the country is located near the equator, there is little seasonal change in the daily load profile throughout the year. For the entire year, sunrise is between 6 and 7 a.m. while sunset is between 6 and 7 p.m. The daily load peaks at about 13 MW after sunset between 7 and 9 p.m. The daily energy demand is about 240 MWh.

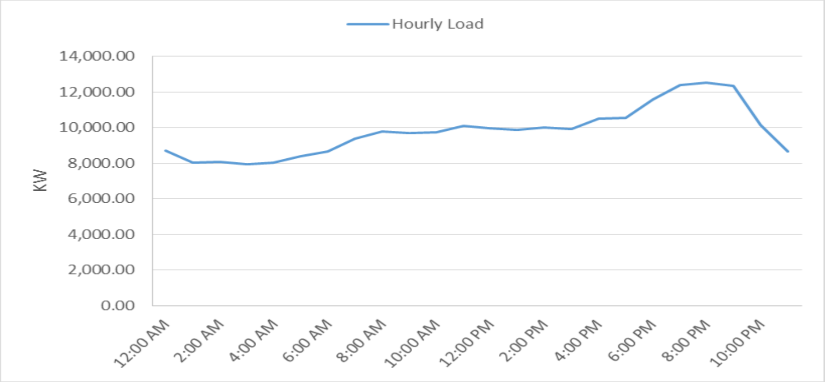

Fig. 5 Typical daily load profile in the airport area

To enhance energy independence, indigenous energy source should be utilized as much as possible. Rwanda has an abundant source of methane in Lake Kivu but the utilization of this resource is still in its beginning stage and there are technical challenges to overcome [28].

Although Rwanda is located near the equator, its solar energy resource is quite moderate due to cloudiness. The solar irradiation levels throughout the year are shown in Fig. 6 [27]. Because the country has little seasonal change, the amount of solar energy received daily is relatively constant all year around. The average solar irradiation is between 4.5 and 6 kWh/m^2 per day with a sky clearance index between 0.45 and 0.65. Variations are caused by the different degrees of cloudiness. Since the peak load occurs after sunset, solar energy cannot be used to meet the peak load directly and energy storage system is needed.

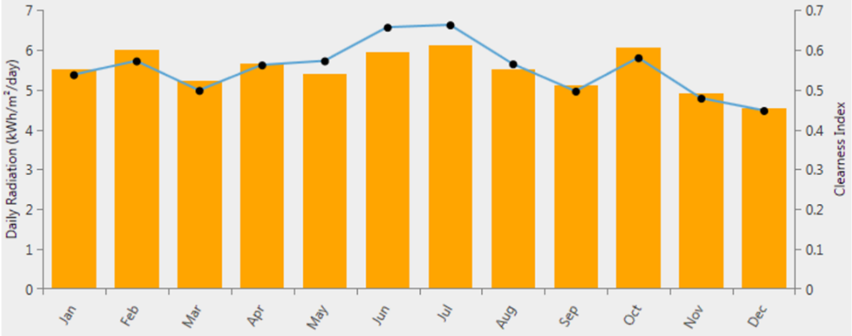

Fig. 6 Profile of solar irradiation availability in Kagali

Several options of micro grids have been designed and analyzed. These options are designed so that the Airport Microgrid can operate in the stand-alone mode at any time and all loads will be served. All options utilize the basic framework shown in Fig. 1. The HOMER software [29] was used to perform the preliminary design and analysis. Table II shows three major options.

Table II. Comparison of microgrid designs

Microgrid System Design	Levelized Cost Of Energy ($/kWh)	Net Present Cost (Million US$)	Operating Cost (Million US$)	Capital Investment (Million US$)
Option I : DG only	0.409	406.0	34.4	7.0
Option II : DG + PV + ESS	0.382	379.5	30.5	26.1
Option III : PV + ESS	0.262	257.5	0.5	251.7

Option I: DG only

This design involves a combination of diesel generators of different sizes with a total rating of 13.935 MW (2.9 MW of CAT 1450, 1.635 MW of CAT 545 and 9.4 MW of CAT 4700). The price of diesel fuel used for the design is $1.4/liter. The operating cost that includes fuel cost is about $34 million. The capital investment is about $7 million.

Option II: DG+PV+ESS

This design involves 13.5 MW of diesel generators (2.90 MW of CAT 1450 and 9.4 MW of CAT 4700), 8 MW of photovoltaic (PV) arrays and a 1.2-MW 2.4-MWh of ESS. Since the peak load occurs after sunset, the peak load is met by using the diesel generator and the ESS together. The efficiency of the PV arrays is 20% and the PV system cost is $3,000/kW. The ESS used is based on the Aqueous Hybrid Ion (AHI) intercalation battery system (roundtrip efficiency is 92%) provided by Aquion Energy with a levelized energy cost of about $0.23/kWh. The operating cost drops to $30.5 million but the capital investment is increased to $26.1 million.

Option III: PV+ESS

This design includes 72.5 MW of solar PV arrays and 36.4 MW of ESS with a storage capacity of 291.2 MWh. The peak load is met by the ESS alone after sunset. The solar arrays are sized so that they can supply the load during the day and charge up the ESS enough so that the ESS can supply the load from sunset until the next morning. To accommodate the rate of charging during the day, the power rating of the ESS is much higher than that required by the peak load. For this design, the operating cost is reduced to $0.5 million but the capital investment is increased to $272.4 million. There is enough land around the airport that can accommodate the required PV arrays.

Three major events are simulated to study the impact of the Airport Microgrid on resilience enhancement of Kigali. The first event is the outage of the northern line. Using power flow analysis and contingency analysis, simulated results are shown in Figure 7. With the outage of the northern line, not only will Kigali be in blackout but the ensuing overloading of the other lines will cause them to be taken out in cascade and result in blackout in many parts of the country. As shown in Table III and Table IV, the AA-ERI and the KC-ERI are both zero for this event.

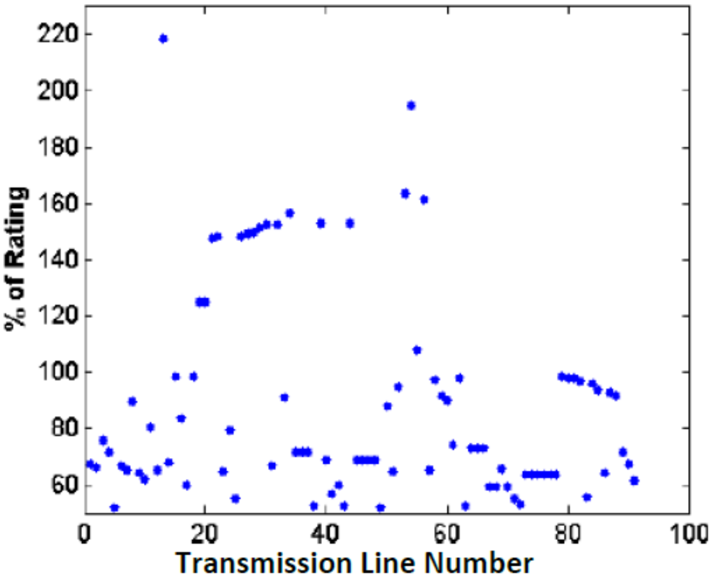

Fig. 7 Line loading when the northern line is in outage

Table III. Airport area event resilience index (AA-ERI) with and without the airport microgrid

Event	AA-ERI Without Airport Microgrid	AA-ERI With Airport Microgrid
Outage of Northern Line	0.0	1.0
Outage of Southern Line	0.0	1.0
Outage of Northern & Southern Lines	0.0	1.0

Table IV. Kigali city event resilience index (KC-ERI) with and without the airport microgrid

Event	KC-ERI Without Airport Microgrid	KC-ERI With Airport Microgrid
Outage of Northern Line	0.0	1.0
Outage of Southern Line	0.0	1.0
Outage of Northern & Southern Lines	0.0	1.0 *

* The loads served by the 70-kV line outside of Kigali need to be shedded.

In the presence of the Airport Microgrid, the fast switch at the PCC will open quickly upon detection of the outage of the northern line. The electrical loads in the airport area are then electrically disconnected from the rest of the power system in Kigali and the Airport Microgrid will be operated in the stand-alone mode. The power sources inside the Airport Microgrid, using anyone of the three options mentioned above, will keep all the electric loads inside the airport area served. As shown in Table III, the AA-ERI is unity for this event.

With the electric loads in the airport area disconnected, the rest of the electric loads in Kigali can be served by the southern line and local generation even when the northern line is in outage. As shown in Table IV, the KC-ERI is also unity for this event. Figure 8 shows that the loading for almost all the transmission lines are within their respective ratings (the only line with 140% loading is geographically far away from Kigali and has little impact on Kigali). Not only all the electric loads inside Kigali are served but most of the country also avoid a blackout.

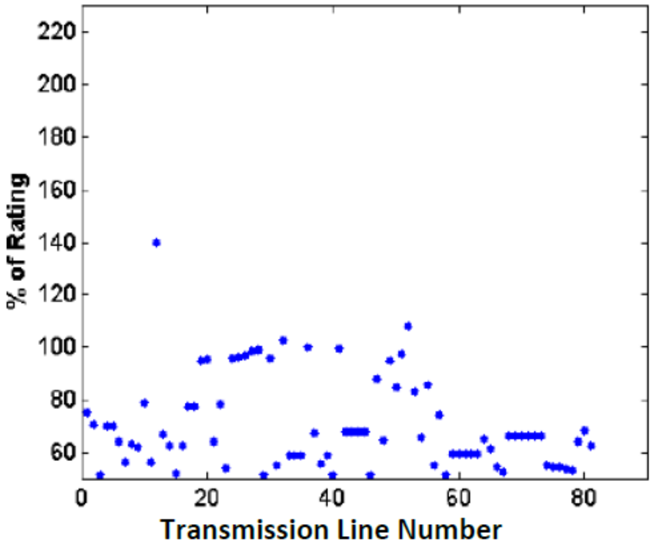

Fig. 8 Line loading when the northern line is in outage and the Airport Microgrid is operated in the stand-alone mode

The Airport Micro grid has similar impact when the southern line is in outage. For this event, the AM-ERI and KC-ERI can be changed from zero to unity by using the Airport Microgrid in the stand-alone mode. In the event that both the northern line and the southern line are in outage simultaneously, the AA-ERI can be changed from zero to unity by the Airport Microgrid alone. The KC-ERI can also be changed from zero to unity but additional shedding of loads connected to the 70-kV line need to be performed in addition to the stand-alone operation of the Airport Microgrid.

Among the three options shown in Table II, the DG only option has the highest levelized cost of energy (LCOE), the highest net present cost (NPC), the highest operating cost but the lowest initial capital investment. The option of PV+ESS is exactly the opposite while the option of DG+PV+ESS is in between.

Rwanda generates over 40% of its electricity from burning diesel fuel and heavy fuel oils [26]. Despite falling oil prices in recent years, transport costs keep the power generation costs high. According to the United

Nations and World Bank, the price of electricity in Rwanda is about $0.24/kWh, even with substantial government subsidy [26, 28]. The LCOE of $0.262 for the PV+ESS option is only 9.2% higher than the current price but without government subsidy.

Rwanda recently installs an 8.5-MW solar PV system at a capital cost of $23.7 million [30]. The host system buys power based on a 25-year power purchase agreement but has to absorb all solar fluctuations. The $251.2 million price tag of the PV+ESS option includes a 72.5-MW solar PV system and a 36.4-MW 291.2-MWh ESS system. With the ESS system, the PV+ESS option not only can take care of all solar fluctuations but also provides more flexibility and other benefits in system operation [18].

The HOMER software computes the NPVs of different designs for comparison. It provides the cost of a microgrid by focusing on the microgrid alone. However, there are important factors that are not captured by the HOMER results shown in Table II. Below are two important aspects that can justify the Airport Microgrid.

Energy independence - With the PV+ESS option, the operation of Kigali, the capital city of the landlocked country of Rwanda, can rely on its local solar energy resources without depending on imported diesel fuel. With the Airport Microgrid, the Kigali International Airport can be kept operational continually during a natural or man-made crisis without worrying about whether the amount of diesel fuel is adequate. Although the benefits associated with energy independence are obvious, these benefits need further study to quantify. Support of SMEs and economic development - The SME sector comprises 98% of the businesses in Rwanda and 41% of all private sector employment [6]. A reliable and resilient electricity infrastructure is critical to support the development of SMEs and, more broadly, the economic development of the entire country. More data need to be collected and analyzed to quantify these benefits.

Although Option I and Option II requires lower capital investment, Option III provides more benefits, especially in terms of national security, energy independence and economic development.

V. Implications for Policy and Planning

Currently, enterprises have two choices to obtain electricity: the utility power grid and self-generation. In Africa, self-generated electricity is 313 percent more expensive on average than electricity from the grid [31]. The main victims are the informal firms and the SMEs, which play an important role in the economy of developing countries in terms of the generation of employment and wealth.

Micro grids provide a third alternative. A community that wants high-quality power can group their loads together (as loads shown in Figure 1). Instead of one generator for one firm, the businesses in the group can share the power sources and the ESS, and benefit from the economy of scale. New pricing schemes may be formed to meet the needs of different businesses. For example, electric loads within a microgrid may be separated into priority loads and deferrable loads [14]. Enterprises with priority loads pay more and receive electric power at the time they prefer and at high power quality. Enterprises with deferrable load pays less but will still receive electricity that serve their needs. Policy needs to be formulated to encourage the building of microgrid and the formation of business models to incentivize investors in providing funding for microgrid projects.

Long term economic growth and competitiveness of many African countries are hampered by frequent and lengthy power outages. Power outages occur at the average rate of 56 days per year. Many firms operate their own diesel generators at two to three times the already high tariffs with attendant environmental costs. On average the cost of load shedding to the economy is equivalent to 2.1 percent of GDP [32].

Fig. 9 shows the general tradeoff relationship between outage costs and the costs of equipment that enhances reliability and resilience. As the capacity of enhancement increases, the frequency and duration of outages decrease but the cost of enhancement increases. The total cost, which is the sum of the outage cost and the enhancement cost, reaches a minimum value at a certain level of enhancement capacity.

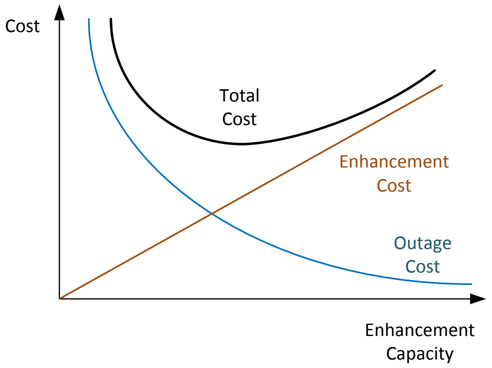

Fig. 9 Tradeoff of outage and enhancement costs

It is important to include the outage costs in the computation of total cost in the planning process. Planning tools such as HOMER only considers the least-cost design for enhancement. Outage costs can be obtained through systematic collection of outage data and survey of businesses on the estimated losses associated with outages.

System planning needs to consider the costs of power outages to the enterprises and the costs to the society at large [8]. Even though SMEs in the formal sector can benefit greatly from the positive impacts of microgrids, various entities in the informal sector of the economy can appreciate even more because most of them simply cannot afford their own generation for various reasons. The informal sector makes up a significant portion of the economies in developing countries and provides many economic opportunities for the poor [33]. Because of the improvement in power quality and reliability through the use of microgrids, enterprises in developing countries can meet international quality standards for participation in export markets. This provides another impetus for job creation and economic development. The societal impacts of microgrids should be included in the planning process.

VI. Conclusions

This paper demonstrates how a microgrid may be used to improve the resilience of the electric power system serving Kigali against blackouts. As shown in Section IV, the Airport Microgrid not only can serve all the electric loads inside the airport area during major disruptive events, but the electric loads in the entire city of Kigali outside the airport area are also kept being supplied. A new resilience metric, the event resilience index (ERI) has been introduced to gauge the impact.

Several features of microgrids that are especially pertinent for developing countries have been presented. In addition to the two existing modes – utility grid and customer-owned generation – microgrids provide a third alternative for customers to obtain electric power. Through microgrids, electric power service can be more reliable and resilient, and this will enable growth of the economy, especially in the sectors of informal firms and small and medium-sized enterprises. Through microgrids, high penetration of renewable energy can be integrated into electric power systems without introducing significant adverse effects due to the variability of renewable energy. This is especially helpful in enabling developing countries to achieve energy independence. Through microgrids, higher levels of reliability and resilience can be achieved without building costly redundant transmission infrastructure.

Microgrids need to be included in the urban energy planning process. System planning needs to consider the total cost that consists of cost of power outages to the enterprises, the costs to the society at large and the costs of microgrids. Policy needs to be formulated to encourage the building of microgrids and the formation of business models to incentivize investors in providing funding for microgrid projects.

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