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Using microgrids featuring PV panels and batteries connected to the grid to improve the reliability of a low-voltage feeder in Kinshasa

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Abstract

This article presents an approach for the design of an electricity grid using microgrid (MG) with photovoltaic panels and batteries connected to the low voltage network. The objective is to quantify the potential benefits of the microgrid in terms of reliability and ensure the availability of electrical energy to reduce consumer stress. The cabin is unreliable, fault and/or load shedding is frequent and untimely with peaks of the network. Based on the assumptions, the design of the microgrid is based on reliability criteria such as the probability of pressure loss, the cost of energy and economic efficiency. The parameters of the model are such as the solar irradiation, the efficiency of the PV module, the temperature, the energy needs of the consumer. In the last pages, the simulations are carried out with Matlab and PVSyst software and the cost of the energy not supplied is calculated at 2.13€/kWh. The economic efficiency of the microgrid is evaluated using the ratio of energy lost during grid failure/load shedding to microgrid cost at 46%. The reliability considering the support microgrids is evaluated at 53%.

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Keywords: Microgrid,Sizing,Reliability,Fault, Load Shidding,Renewable energy,Integration.

1. Introduction

Electricity distribution network in the Democratic Republic of Congo (DRC) is not sufficiently developed. The current peak is of 700 MW. The city of Kinshasa is located near -4.43_latitude and 15.26_longitude and at 445m altitude. Its area is 9 965 km^2 with 12 071 000 inhabitants. Depending on the location and due to good sunlight conditions, the solar irradiation is between 3.5 and 6.75 kWh /m^2/day. Thehe goal of paper is to quantify the potential benefits of using microgrid to improve the reliability of a feeder of low voltage distribution network. Microgrids are

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small, decentralized structures with a demand for consumption and local means of production. In [1] the wind turbine generator (WTG), photovoltaic (PV) and battery storage system (BSS) are used in order to improve the reliability of the existing network and reduce the cost of energy (COE) and the annualized cost of the system (ACS).

Reliability is the probability that a power system will meet the load requirements at any time [2]. To achieve this goal, photovoltaic solar panels and batteries are integrated into a power system. In [6] the reliability evaluation parameters are indicated for our case. Availability of a power system is typically measured as a factor of its reliability as reliability increases, so does availability [3]. However, the contributions of this work relate to the following aspects:

- To reduce the dependence of the main network and to influence the energy mix. To reduce consumer stress and downtime due to power outages. The main objective is to quantify the potential benefits of the microgrid in terms of reliability. The model of the proposed system is shown in figure 1 above. Two configurations are possible. The configuration on the left indicates the operational network. The configuration on the right shows the non-operational network. The batteries are charged by photovoltaic solar panels and by the networks. The inverter placed on the network interface is synchronized with the voltage and frequency provided by the network. The microgrid is placed at the end of the low voltage network (LV).

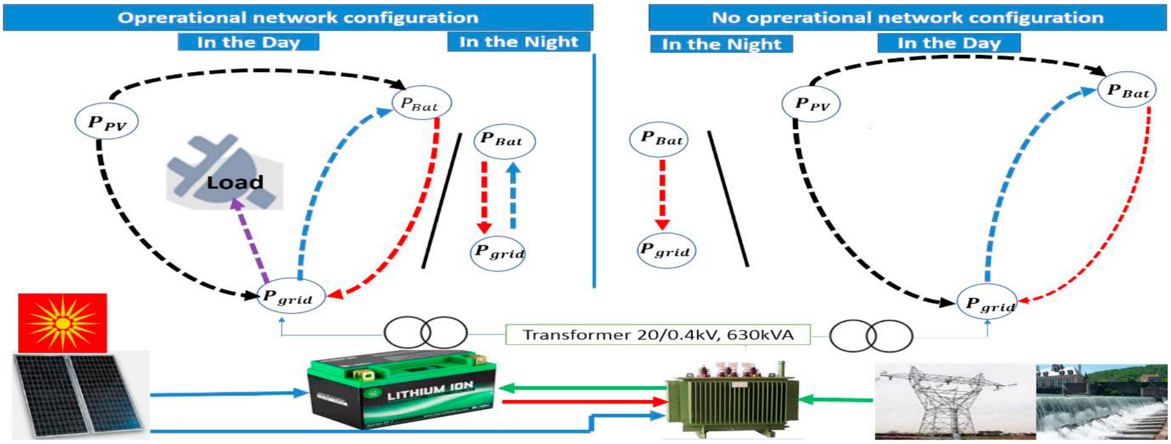

Fig. 1. Flexible model of microgrid

Section 2 gives the methodology. Section 3 introduces sizing of microgrid components. Section 4 describes the system design criteria. Sections 5 and 6 indicate objective function and the results and discussion. Section 7 gives the conclusion.

Nomenclature

Q_{loss}	Energy not supplied	CQ_{loss}	Cost of energy not supplied
$\bar{P}_i$	Average load load in the interval i	$\delta_{r,i}$,	Duration of interval i for number of intervals during r_j.
n	Horizon of the system in year y;	LLP	Loss of load probability
LCE	Levelized Cost of Energy	η_{min}	Fraction minimum energy demand solar source;
E_y	Generated energy in [€/Wh] in year y;	M_y	Operation and maintenance expenditures in in year y
r	Discount rate in %;	δ	Degradation factor (0.2-1.0%)
I_y	Investment	STC	Standard test conditions
LV	Low voltage	$d_{t,n}$	The net electricity demand of household
S_t^{Bat}	Initial SoC is the SoC at tth hours;	p_i	Installed power of the household
η_{ch}	Efficiency of charging $\in [0,1]$	S_{t+1}^{Bat}	The SoC at the next hour;
E_t	Total production available at the time i	η_{dich}	Efficiency of discharging $\in [0,1]$
$d_{t,i}$	Energy demand at time i	d_t	Load demand at the time i;
$\Delta_{t,i}$	Variation of time between t and $t+1$	$E_{t,i}$	Energy produced at time i
x, b, beq, lb and ub: Vectors;		C(x), Ceq	Non-linear constraints
A and Aeq Matrix;		F(x)	Function that returns a scalar;
P	Probability that the power P_{i1} is microgrid can be greater than load		

2. Methodology

The methodology used in this work is based on assumptions and sizing criteria. These assumptions and criteria are based on stochastic variables such as solar irradiation and electricity demand. These two factors lead to the sizing of microgrid to ensure energy production. The assumptions and the sizing criteria corresponding to the load profile are defined:

- The cabin is not reliable. It is located at the end of the line low voltage 0.4 kV at a radius of 500 m;
- PV generates energy between 8:00 and 18:00. We considered the mow irradiation of 3 kWh / m^2/ day for sizing;
- The effects of stability are not considered. The ability to operate in parallel with the network or independently of the network is not discussed. Microgrid is in the town of Kinseso in Kinshasa. The techno-economic design of the system is achieved using the concept of power loss and levelized cost of energy as technical and economic criteria.

2.1. Load Profile

Daily load profiles of a household (appliances and their daily use) in Kinshasa and a commercial activity are from 496.55 Wh/day and 2873.08 Wh/day respectively. We consider a total consumption of 50 households and a small commercial sector connected to a transformer 20/0.4 kV, 630 kVA. Consumption of the load is determined according to the installed power $\boldsymbol{p_i}$ of the household. The net electricity demand $\boldsymbol{d_{t,n}}$ is the difference between the local consumption $\boldsymbol{c_t}$ and the available power installed, $\sum_{i=1} \boldsymbol{p_i}$ follows (1),

$$d_{t,n} = c_t - \sum_{i=1} p_i \tag{1}$$

where $p_i = \xi_i \lambda_i$ index i = 1,2,3 refers to both household, small and medium-sized enterprises, and public lighting; ξ_i number of households by installed capacity and λ_i is the composition factor, $\lambda_i = s_i \mu_i h_i$. However, s_i and d_i are coefficients of simultaneity and diversity respectively and $h_i$usage factor that considers that not all receivers are used at full load.

3. Sizing of microgrid components

3.1. PV Power Generation

Sizing criteria for photovoltaic panels include the specific size of the PV in Wp, the $\boldsymbol{A_{PV}}$ area in $\boldsymbol{m^2}$, and the solar irradiation I in kWh/$\boldsymbol{m^2}$ at 25 ° C under standard test conditions (STC). Considering the performance degradation factor $\boldsymbol{\delta}$, we write as follows (2),

$$P_{PV} = (1 - \delta) A_{PV} I \eta_{PV} \tag{2}$$

to ensure that the power generated is equal to the power consumed or because of fluctuation photovoltaic solar panels, we use the energy storage system.

3.2. Energy storage battery

The choice of battery storage and its capacity are justified by direct compatibility with PVs, energy storage for long periods of time (hours, days…) and industrial availability with high potential. In this article, the energy storage ensures the fluctuation of the production of PV and the absence of it during the night. Basically, the minimum energy storage capacity can be calculated as follows (3),

$$C_{Bat}^{min}[Wh] = \mathrm{\mu_j}.\,24[\text{hours}].\,\mathrm{E_{load}}[\mathrm{W}] \tag{3}$$

for example, 3.3MWh(=0.8x24x177kW) where autonomy μ_j is 0.8 days for a load of 177 kWh and a battery of 230 Ah. This indicates that the need for energy storage capacity is not only due to availability, but also proves how capacity affects availability. However, the battery is charged and discharged depending on the state of the network and the PV system as well as the behavior of the consumer. The SoC of battery bank at any time t_1 depends upon state of charge in the previous moment t_0 and the sequence of generated power and load demand levels in the time interval $t_1 - t_0$.

The SoC at time t +1 of the battery can be determined by knowing the SoC of the battery at time t. As a result, compared to the SoC at time t, the energy storage dynamics (charge/discharge to/from the battery) of the microgrid is formulated as follows (4) and (5),

$$S_{t+1}^{Bat} = S_t^{Bat} + \eta_{ch}\left[P_{PV,t} + ©P_{grid,t}\right] - \frac{1}{\eta_{disch}}\left[P_{Bat,t}\right] \quad (4)$$

$$S_t^{Bat} = S_0^{Bat} + \eta_{ch}\sum_{i=0}^{t-1}\left[P_{PV,t} + P_{grid,t}\right] - \sum_{i=0}^{t-1}\frac{1}{\eta_{disch}}\left[P_{Bat,t}\right] \quad (5)$$

4. System design criteria

4.1. Loss of load probability, LLP vs Energy not supplied

Two indices for the reliability measure are the unavailability (the probability of loss of load, LLP) [8] and the energy not supplied to consumers. LLP is the ratio of the energy not supplied by the system to the total energy required, LLP=Total energy deficit/Total energy demand at time step $\boldsymbol{i}$, e.g. hours:24($\boldsymbol{i} = \mathbf{1}, \dots, \mathbf{24}$) of equal size. The availability of the system such as $\mathbf{E_t(1 - LLP) \geq \eta_{min}.\, d_t}$. In other words, availability **A** of microgrid can be defined as the probability that sufficient power can be supplied to the load such that $\boldsymbol{A = Pr[P_{i1} \geq Load]}$. The goal is therefore to improve reliability and therefore reduce the probability of losing the load. Formally as follows (6),

$$\mathrm{LLP} = \frac{\sum_{i=1}^{24} \mathrm{d_{t,i}} - \mathrm{E_{t,i}}.\,\Delta_{\mathrm{t,i}}}{\sum_{i=1}^{24} \mathrm{d_{t,i}}.\,\Delta_{\mathrm{t,i}}}\,[\%] \quad (6)$$

and energy not supplied Q_{-loss} may be due, for example to the load shedding/fault of the network such as (7).

$$Q_{loss} = \sum_{i=1}^{I} \bar{P}_i\, \delta_{r,i} \quad \text{or} \quad Q_{loss} = \sum_{i=0}^{24h} \Pr(E_{t,i} < d_{t,i})(d_{t,i} - E_{t,i}) \quad (7)$$

The cost of energy not supplied CQ_{-loss} is used by the utility to monetize the effect of power failure in a power system where the value of the lost energy is estimated[4]. It is important to plan the power system to achieve desired reliability that can reduce the social and economic costs to consumers (8),

$$\mathrm{CQ_{loss}} = \frac{\mathrm{k_{res}.C_{D,res}} + (\mathrm{k_{com}.C_{D,com}}) + \mathrm{C_{i,tot}}}{\sum_{t=0}^{h} \mathrm{CQ_{loss}}} \quad (8)$$

4.2. Economical criteria vs levelized energy cost (LEC)

Planning the microgrid for any production and consumption scenario leads to the initial investment cost and considers the economic aspects. This cost is called the Levelized Cost of Energy (LEC) [4][5] as defined below (9),

$$LEC = \frac{\dfrac{I_0 + \sum_{y=1}^{n} I_y - M_y}{(1+r)^y}}{\sum_{y=1}^{n} \dfrac{E_y(1+\delta)^y.\,\Delta_y}{(1-r)^y}} \quad (9)$$

5. Objective function

The selected objective function aims at improving the reliability and economically satisfy the load demand. The objective function is used for minimizing a levelized energy cost (LEC) criterion[6][7] where energy production and demand are known. LEC is a cost measure of different power generation technologies. However, it must be ensured that the load is served according to the criterion of reliability (10),

$$\min_{LLP+Q_{loss}+LCE} \sum_{i=1}^{n} (LLP + Q_{loss} + LEC) \tag{10}$$

s.c

$$\sum_{i=0}^{n} Q_{loss} =\leq -d_t - \sum_{i=1}^{n} P_{PV,i} + P_{Bat,i} + P_{grid,i} \tag{10.1}$$

$$P_{grid,t} + \frac{\sum_{j,k} P_{PV,j} + P_{Bat,k}}{\eta_{i.k}} \leq A_{j,k} \tag{10.2}$$

$$\sum Q_{loss} \leq 0 \text{ and } -Q_{loss} \leq c_t \tag{10.3}$$

The objective function (10) can be realized by using the function fmincon in optimtool in MATLAB as presented as follows (11),

$$\min_x f(x)\,, \text{s.c} \begin{cases} C(x) \leq 0 \\ Ceq(x) = 0\,; \\ A.x \leq 0 \end{cases} \begin{cases} Aeq.x = beq \\ A.x \leq 0 \\ lb \leq x \leq ub \end{cases} \tag{11}$$

6. Results and discussion

This section is introduced to quantify the benefits of renewable energy in the form of microgrid in terms of reliability. The idea is to reduce the unavailability of the electric current as a result of faults and thus improve the reliability of the main network. Load peaks are observed between 8:00 am and 10:00 am, at 6:00 pm and at 9:00 pm. Table 1 below gives the energy consumption of the consumer for 24 hours. Out of the 12 columns, 3 columns indicate the hours of operation, 3 columns of load in normal operation and 3 columns of loads with faults. The simulations use Matlab tool, considering that the network is either operational, either non-operational.

Table 1. Vector load household on network with faults.

Hours	Load	L.Fault	Hours	Load	L.Fault	Hours	Load	L.Fault	Hours	Load	L.Fault
00	110.4	110.4	06	92.8	92.8	12	84.5	84.5	18	227.1	00
01	110.4	110.4	07	75	75	13	75	75	19	155.7	155.7
02	75	75	08	198.5	00	14	105	105	20	145.7	145.7
03	75	75	09	118.5	118.5	15	75	75	21	101.3	00
04	75	75	10	75	75	16	75.6	75.6	22	75	75
05	75.5	75.5	11	105.8	105.8	17	115.1	115.1	23	75.5	75.5

In figure 2 below, the breakdowns occurred between 08:00 am and 10:00 am, at 6:00 pm and at 9:00 pm. The failures result in a loss in terms of energy of about 526.9 Wh (198.5Wh, 227.1 Wh and 101.3Wh) respectively. The loss of 526.9 Wh is offset by the use of microgrid by ensuring the availability of electric current and reducing the stress of the consumer. The monetary value of the loss of load caused by the power fault is assumed to be about €13Wh. In figures 1 and 2 above the blue colors indicate the microgrid load relative to the network. In Figures 1 and

2 below the blue colors indicate the microgrid load relative to the network. Thus, LLP corresponding to the loss of load is 8%, 9% and 4% between 8:00 am, at 6:00 pm and at 9:00 pm respectively. The cost of energy produced, CQ_E is about 1.60 €/Wh and energy not supplied, CQ_loss is about 2.13 €/Wh.

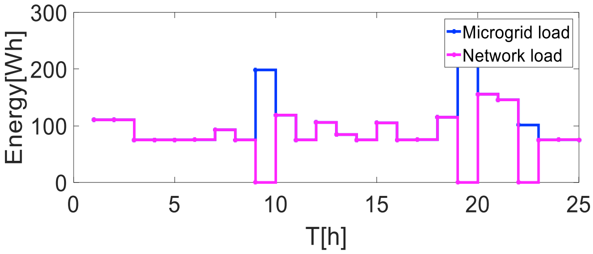

Fig. 2. Network fault (Household sector)

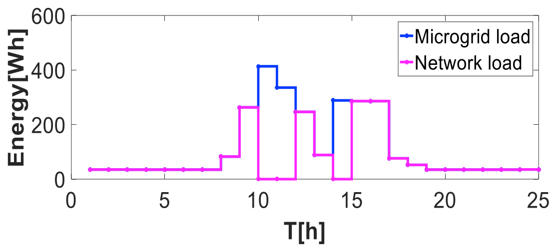

Fig. 3. Network fault (commercial sector)

The reliability of the network by integrating microgrid is evaluated at 53% and the optimization technique makes it possible to reduce the LEC evaluated to 0.09€/Wh figures 4 and 5 respectively .

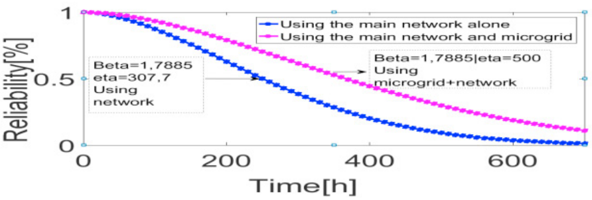

Fig. 4. Reliability

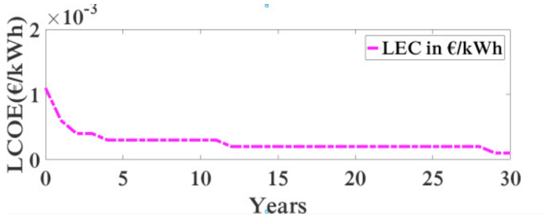

Fig. 5. LEC

The results of this study are similar to those of previous studies. Comparative analysis done with other studies shows that in [1] cost of energy, COE or LEC, is estimated at 0.395 €/kWh and expected energy not served, EENS or CQ_loss is estimated at 14.277 MWh/y. However, in [2] COE is about 0.665 €/kWh. Their results show that the loss of values of load probability, expected energy not supplied can be used to improve the reliability of the power system. These values decrease with the integration of renewable energies in the form of a microgrid.

7. Conclusion

The objective is to quantify the potential benefits of the microgrid in terms of reliability and reliability of production at the lowest cost possible. The applied methodology of this article can be used with the objective of improving the reliability of the power supply. The economic efficiency of the microgrid is evaluated using the ratio of the energy lost during the network failure.

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