APPROACH FOR SIZING AND DESIGNING AN OPTIMAL MINI-GRID FOR RURAL ELECTRIFICATION IN MADAGASCAR

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ABSTRACT

Rural electrification plays a significant role in promoting development in isolated areas. This paper presents new design of a small electric distribution system which called mini-grid adapted to these areas. The main objective is to design an optimal configuration of a mini-grid in such remote rural area with a given statistical and geographical data. Test is carried out on a rural region having 7387 households spread over 19 villages in Madagascar. After sizing power demand in each village, and the distance separated each one, near optimal configuration is validated by evaluating line loss and voltage profile in accordance with acceptable range. Loss estimation, voltage calculation for each configuration are calculated by Newton Raphson load-flow analysis.

Keyword : *rural electrification, mini-grid, sizing, design, optimal configuration, isolated area*

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1. INTRODUCTION

In recent decades, we have seen a new international energy policy that is moving towards rural electrification by promoting renewable energies and other sources. Several private operators and electrification agencies have taken the opportunity to use different kind of energy to meet local demand. Most of them focused only on energy production and implemented autonomous production sites. Besides, they use some energy produced to supply the isolated area and sell some part of it to be injected into the main grid. It means that their production systems become a Distributed Generation (DG). Instead of choosing an appropriate technology for electricity production, focusing on distribution system is one of the best solutions to meet energy needs in every rural villages. Decision-making for this system aims to reduce mismatch between production and demand in primary distribution circuit. Four main parameters (P,Q,V, δ) characterize each bus (generator bus and load bus) that are respectively the active power, the reactive power, the voltage magnitude and the voltage angle; whereas impedance Z, admittance Y, current and power transit between two buses, are the characteristics of a branch. Appropriate sizing of electricity demand in each village (load bus) and optimal design of the whole system are then required.

New approach for sizing and designing small distribution system is presented in this paper. The main objective is to find the initial configuration of a mini-grid design by means of given statistical and geographical local data to generate bus and line data that can be used in load flow study.

Approach begins with data collection, sizing electricity demand in each village and estimation of energy production. Then before proceeding to the technical optimization, analysis by Newton-Raphson load flow(NRLF) method are required in order to assess first the loss in each branch, and second the generation in each bus. Two main criteria such as power losses minimization at branch, and best voltage profile at bus are our objective function that leads to near optimal configuration.

To test the efficiency of this approach; investigation, simulation and data collection from remote sites in rural commune of Antsahalava, district of Antanifotsy/ Antananarivo/ Madagascar are carried out under Matlab R2015a. Geographical location is determined by ArcGiS 10.5.

2. OVERVIEW OF RURAL ELECTRIFICATION SYSTEM IN THE WORLD

2.1 Statistics of rural population unelectrified

Many areas in the world have lacked of electricity because the supply of electric power has always been insufficient. According to the assessment of the World Bank in 2008, there are 260 million rural households in the developing world without access to electricity [1].In another assessment, currently 1300 million people around the world do not have access to electricity, and 85% of them live in rural areas[2]. In particular, rural electrification rate on such countries shown at chart 1 (like India, Nigeria, Bangladesh) are still very low. Also, in sub-Saharan Africa, IEA estimated that 599 million people are still lack of electricity access in 2011. [3]

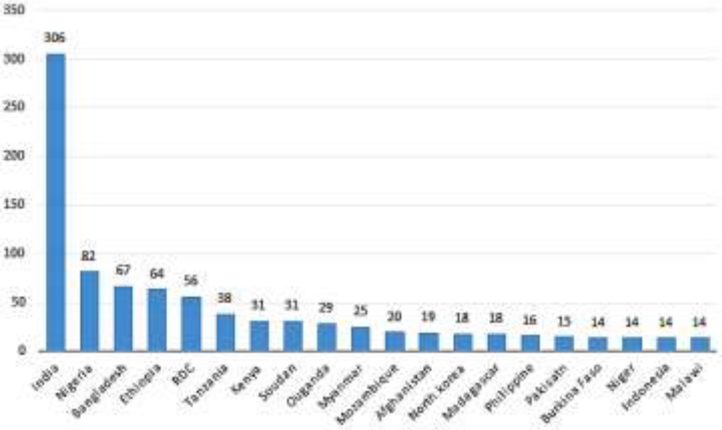

Chart -1 Populations without access to electricity (in Millions of people)[4]

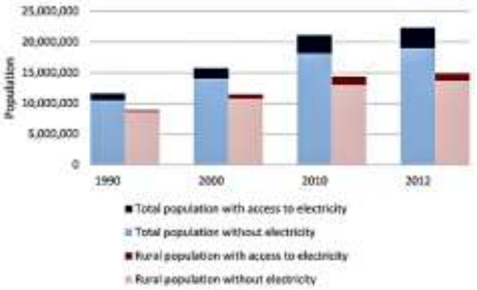

Chart-2:People with access to electricity in Madagascar[5]

In Madagascar, access to electricity remains very low. Most of Malagasy people live in rural areas which represent 65% of the population with low electrification rate (less than 10%) [6;7]. Among the 1578 communes, 400 are electrified by national grid and others private operators that is about 25% [8]. It means that 75% of commune do not have access to electricity.

2.2 Different kind of energy system for off-grid area

The statistics in the chart 1 and chart 2 show that the number of populations without access to electricity need more energy supply, so that the world cannot depend only on limited conventional sources to meet energy demand. Several types of electricity generation systems have been observed in isolated area. The choice of system depends on local energy resources whether renewable or not. There are many rural households that used small generators (500W–5 kW). Some people used traditional bioenergy (biomass and biogas) to meet basic energy needs and lighting. Nevertheless, recent statistics for rural electrification show that the use of renewable energy technologies doesn't cease to increase in recent years; especially the using of photovoltaic system [9]. Renewable energy systems in the forms of photovoltaic solar energy, wind energy, biomass, etc., are put forward as potential solutions [10].

Using stand-alone energy systems with one source, consumers may not satisfy about energy needs. That's why, current researchers, network operators and electrical distributors have been focusing on combination of renewable energies system with diesel generator to form a single system, which is called as hybrid system.

2.3 Concept of an optimal mini-grid design for rural area

Beyond electricity production, distribution system plays important role to the reliability of any electrification project. Many researchers focus only on the expansion of the existing grid infrastructure as an electrification solution for remote area. Either this combination of grid and off-grid option is one of the new technologies to ensure universal access to electricity, this is often encountered by the problem of voltage and frequency[11]. However, previous studies on rural electrification programs in many countries show that a part from renewable energy systems, mini-grid systems are among the dominant technologies used to improve access to electricity in rural communities [12]. Hence, in this paper an autonomous mini-grid for rural area is designed. The term of mini-grid is used because the total power demand in each rural commune in Madagascar is around 2 to 4 MW (under 10 MW).

3. SIZING AND DESIGN METHODOLOGY

3.1 Criteria for optimal mini-grid design

In order to design the best distribution system (either big or small distribution system), the system design engineer must have information concerning the loads and a knowledge of the types of distribution systems that are applicable. Basic principles for power distribution system design include: locations and characteristics of loads, sources of power, distribution and utilization voltages, and distribution equipment (cable feeders) [13].

Basically, Configuration validation requires at least two criteria: - less total power loss
- best voltage profile in each bus

In this research, we come closer to an approach for identifying the line that link each bus. It is constrained by the minimum transit power between each bus at the aim of power loss reduction. The overall active power loss threshold considered acceptable for distribution system should be around 3 to 6% [14]. Also, according to the international standard voltage limit as IEC Std. 50160 [15], lower bound and upper bound of voltage in low voltage and medium voltage electricity distribution systems are 0.9 and 1.1 in p.u, respectively; that is around +/-10% of the base voltage. Therefore, $0.9<V(pu)<1.1$ and $3\%<P_{loss}<6\%$

In addition, generator's placement has a good impact on voltage profile in each bus. So, with the first configuration of mini-grid design, one generator must set up before a load-bus which have a high power demand among all buses. Assume that this generator-bus is also called as slack-bus in our case because resolving load flow problem needs one bus that chosen arbitrarily with a fixed value of the voltage (V, δ).

$$V_{PVbus}=1\text{ pu},\ \Theta_{PVbus}=0°$$

3.2 Electric demand sizing methodology per village

Sizing method consists of site visit, collect of statistical data, surveys and informal interview of local people in every household in each village:

-Household power demand calculation: $$P_{dhv}=\sum_{i=1}^{3}\left(\eta_i.nbm.\sum_{j=1}^{m}P_{aij}N_{aij}\right) \tag{3.1}$$

P_{dhv} [kW] is the total power demand by all of the households in each village
nbm is the total number of households in the village
η_i [%] is the percentage of a household type i ; η_i =number of household type i /nbm
Paij is the nominal power of the device type j in a household type i [kW]
Naij is the number of devices type j in a household type i

-Village total power demand : $$P_{dv}=P_{cn}+P_{dhv} \tag{3.2}$$

where P_{cn} is the total load of community needs. It comes from street lighting, school, church, small commercial market, small and medium enterprises, etc…

3.3 Distribution voltages and cable feeders

Proper voltage level both in Medium Voltage (MV) and low voltage (LV) selection plays a key factor during power system design. In Madagascar, typical values of LV for single-phase and three-phase of power supply are respectively 220V and 380V; whereas MV varies from 5 kV to 63 kV. MV level depends on load characteristics and power transformers. For mini-grid's case , it is not up to 20 kV. Besides, nature of conductor with its section plays a second key factor. Line impedance is characterized by the resistance R and the reactance X.

$$R=\frac{\rho l}{S}\quad\text{and}\quad X=L\omega; \tag{3.3}$$

where ρ: resistivity of the conductor [[Ω.mm²/km] ρ_{cu}=22.1 in 80°C, ρ_{Al}=36 in 80°C
l= Length of the conductor [km] , S= Section of the conductor [mm²] , L= line inductance [H]

3.4 Newton-Raphson method for load flow analysis and loss assessment

Load flow analysis uses simplified notation such as a one line diagram and per unit system, and focuses on various forms of AC power of which the four parameters (P,Q,V,δ) should be involved. Generally, the Newton-Raphson method is widely used for solving non-linear equations. It transforms the original non-linear problem into a sequence of linear problems whose solutions approach the solutions of the original problem.

For the case of load flow problem, the non-linear equations are given by this equation:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} \qquad (3.4)$$

where J1,J2,J3,J4 represent the Jacobian matrix and are respectively

$$J_1=\frac{\partial P_i}{\partial\delta_i},\ J_2=\frac{\partial P_i}{\partial V_i},\ J_3=\frac{\partial Q_i}{\partial\delta_i},\ J_4=\frac{\partial Q_i}{\partial V_i} \qquad (3.5)$$

ΔP and ΔQ are the difference between the specifics value P_{sp}, Q_{sp} and the calculated value of P,Q using the estimates of δ and V in a previous iteration.

$$\Delta P_i^{(k)}=P_{sp}-P_i^{(k)} \quad \text{where} \quad P_i^{(k)}=\sum_{k=1}^{n}Y_{ij}^{(k)}V_j^{(k)}V_i\cos(\theta_{ij}-\delta_i+\delta_j) \qquad (3.6)$$

$$\Delta Q_i^{(k)}=Q_{sp}-Q_i^{(k)} \quad Q_i^{(k)}=\sum_{k=1}^{n}Y_{ij}^{(k)}V_j^{(k)}V_i\sin(\theta_{ij}-\delta_i+\delta_j) \qquad (3.7)$$

Having the new values of δ and V: $V_i^{(k+1)}=V_i^{(k)}+\Delta V_i^{(k)}$; $\delta_i^{(k+1)}=\delta_i^{(k)}+\Delta\delta_i^{(k)}$; (3.8)

new values of transit power P_{ij},Q_{ij} in every branch are obtained. Then active and reactive power losses can be assessed through these equations:

$$P_{loss}=|P_{ij}+P_{ji}| \quad \text{and} \quad Q_{loss}=|Q_{ij}+Q_{ji}| \qquad (3.9)$$

4. RESULTS AND DISCUSSIONS

4.1 Localization of the case study

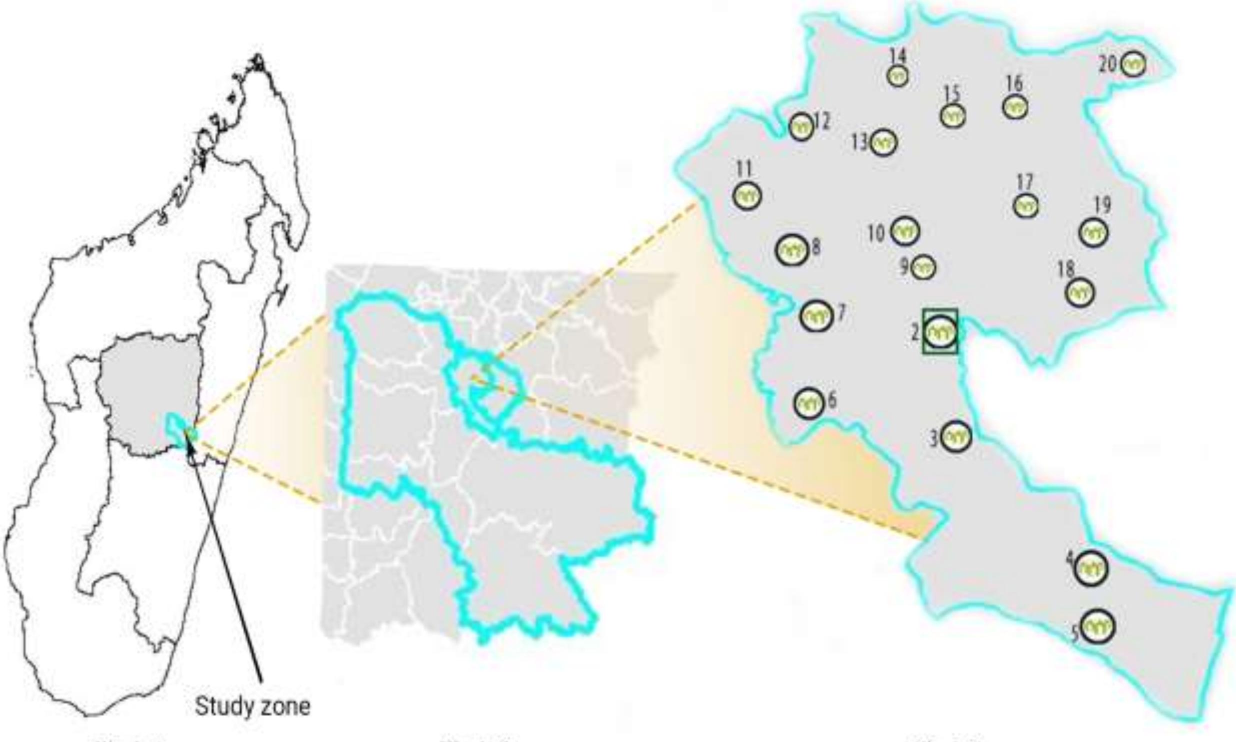

Fig 1-A
Province of Antananarivo

Fig 1-B
District of Antanifotsy

Fig 1-C
Commune of Antsahalava

Fig -1 Geographical location of the case study

According to the statistical data and survey, Rural commune of Antsahalava, District of Antanifotsy/ Madaqascar rural had a total of 39468 population, 7387 households, distributed over 19 villages. We carried out a survey in a village N°16 (cf **Table-2)**, which indicates that on average a household contains 5 or 6 family members. And each household needs power capacity ranging from 30W (min) up to 4000W (max). Among the 410 households, 266 need power under 100W that represent η_1 =65%, 123 need power around 250W (η_2 =30%) and 21 requires power over 400W until 4700W (η_3 =5%). This case shows that we can classify households into three types according to their power demand. Therefore, power demand in each village are calculated through the equation 3.1 and 3.2 but the expression $\sum_{j=1}^{m} P_{aij} N_{aij}$ is replaced by the average power demand shown in Table-1 column 3.

Table-1: Power demand and energy consumption according to household type

Household type	Power demand	Average power demand	Max energy consumption
Type1	30W <Pd ≤ 100W	65W	420 Wh/day
Type2	100 W < Pd ≤ 400W	250W	1576 Wh/day
Type3	400W < Pd ≤ 4700W	2550W	7140 Wh/day

Table -2: Statistical and geographical data of the case study

Villages	Distance from main village [km]	Population number	Average household size	Number of households	η1 (% of household Type 1)	η2 (% of household Type 2)	η3 (% of household Type 3)	Pcn [kW]
Village2 (main village)	0	2046	5	410	51	35	14	15.1
village 3	3	1944	6	324	66	29	5	3.5
village 4	9	2788	6	464	70	25	5	4.3
village 5	10	2244	6	374	65	25	10	4.1
village 6	4	2078	6	350	65	30	5	3.5
village 7	3	1665	5	370	55	35	10	4.4
village 8	4.5	1521	5	330	67	30	3	2.8
village 9	2.5	2141	5	431	60	32	8	4
village 10	3	2296	5	490	52	36	12	3.8
village 11	6	3375	5	680	67	26	7	5.5
village 12	7.5	1888	5	360	64	24	12	5
village 13	7	1169	4	275	66	29	5	3.8
village 14	8	1350	4	310	68	28	4	3
village 15	6	1678	5	370	62	27	11	3.5
village 16	7	2423	6	410	65	30	5	3.8
village 17	5	1212	4	290	70	18	12	3.2
village 18	4	3509	6	585	68	27	5	4.5
village 19	5	1801	5	385	66	28	6	3
village 20	10.5	2340	5	440	62	29	9	4.5
TOTAL		**39468**		**7387**				

4.2 Tests results with two different mini-grid configurations

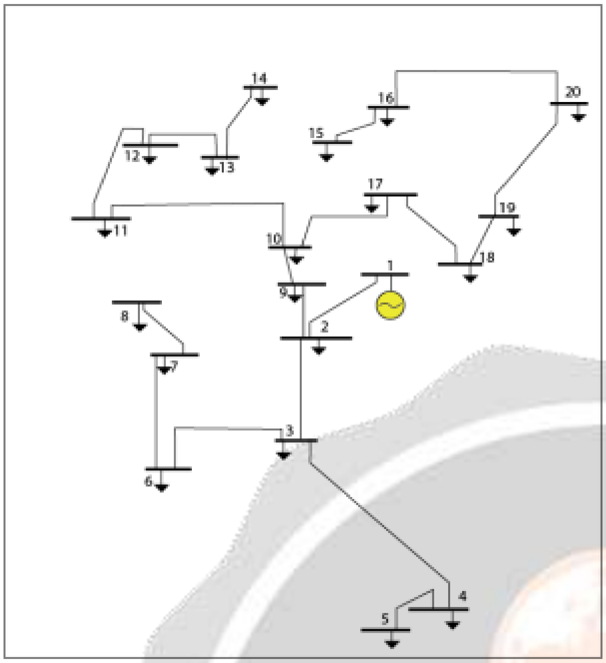

Fig -2-a : one-line diagram, Configuration A

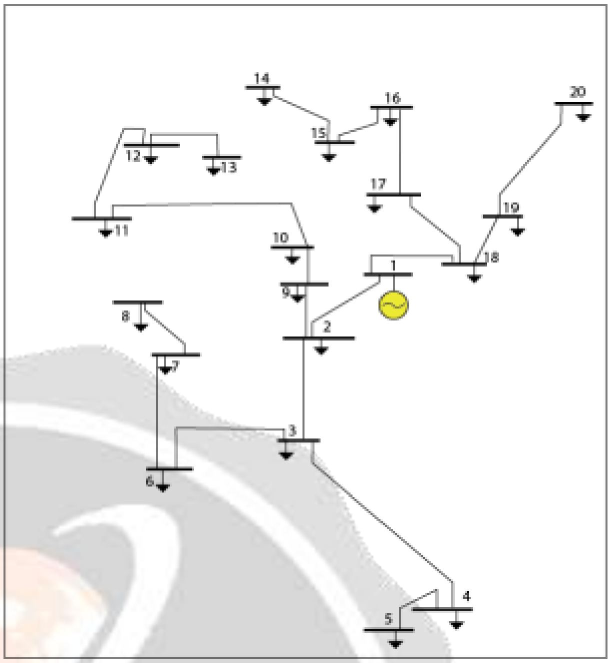

Fig -2-b : one-line diagram, Configuration B

Table-3 Bus data output with demand and generated power

Bus	***Bus type**	**V [pu]**		**V [kV]**		**Angle [pu]**		**Pd** (active power demand) **[kW]**	**Qd** (reactive power demand) **[kVAR]**	**Pg [kW]**		**Qg [kVAR]**	
		Config A	Config B	Config A	Config B	Config A	Config B			Config A	Config B	Config A	Config B
1	1	1	1	5	5	0	0	0	0	2796.8	2.5683	1950.7	1.8621
2	2	0.9458	0.9646	4.7290	4.823	0.8027	0.5465	210.9	158.2	0	0	0	0
3	2	0.9257	0.9449	4.6285	4.724	1.1389	0.8695	82.2	61.6	0	0	0	0
4	2	0.9143	0.9338	4.5715	4.669	1.3366	1.0592	62.1	46.7	0	0	0	0
5	2	0.9131	0.9326	4.5655	4.663	1.3582	1.0799	113.6	85.2	0	0	0	0
6	2	0.9132	0.9346	4.5660	4.673	1.3554	1.0444	138.6	104	0	0	0	0
7	2	0.9059	0.9275	4.5295	4.6375	1.483	1.1661	88.2	66.1	0	0	0	0
8	2	0.9037	0.9254	4.5185	4.627	1.5218	1.2032	133.6	100.2	0	0	0	0
9	2	0.9005	0.9421	4.5025	4.710	1.5305	0.9096	130.4	97.8	0	0	0	0
10	2	0.8922	0.9360	4.4610	4.68	1.672	1.0105	142.2	106.7	0	0	0	0
11	2	0.8621	0.9104	4.3105	4.552	2.2085	1.4476	201.1	150.8	0	0	0	0
12	2	0.8534	0.9034	4.2670	4.517	2.3709	1.5718	199.3	149.4	0	0	0	0
13	2	0.8509	0.9016	4.2545	4.508	2.4187	1.6027	158.7	119	0	0	0	0
14	2	0.8498	0.9696	4.2490	4.848	2.4386	0.4910	60.4	45.3	0	0	0	0
15	2	0.8215	0.9705	4.1075	4.852	2.9602	0.4757	61.4	46	0	0	0	0
16	2	0.8224	0.9720	4.1120	4.860	2.9429	0.4511	102.4	76.8	0	0	0	0
17	2	0.8685	0.9770	4.3425	4.885	2.084	0.3687	99.2	74.4	0	0	0	0
18	2	0.8516	0.9852	4.2580	4.926	2.3905	0.2355	144.4	108.3	0	0	0	0
19	2	0.846	0.9823	4.2300	4.9115	2.4939	0.2830	98.7	74	0	0	0	0
20	2	0.8283	0.9748	4.1415	4.874	2.8285	0.4058	164.7	123.5	0	0	0	0
Total								2392.1	1793.9	2796.8	2.5683	1950.7	1.8621

*Bus Type: (1) slack-bus and generator bus (PV bus), (2) load bus (PQ bus)

Table-4 Line data output and results of power losses by NRLF

Line name	**From bus**		**To bus**		**Distance [km]**		**R [ohm]**		**X [Ohm]**		**Active loss [kW]**		**Reactive loss [kVAR]**	
	c-A	**cB**	**c-A**	**c-B**	**c-A**	**c-B**	**c-A**	**c-B**	**c-A**	**c-B**	**c-A**	**c-B**	**c-A**	**c-B**
Branch 1	1	1	2	2	2	2	0.3820	0.3820	0.1480	0.1480	177.7	76.5	68.8	29.6
Branch 2	2	2	3	3	3	3	0.5730	0.5730	0.2220	0.2220	16.5	15.7	6.4	6.1
Branch 3	3	3	6	4	3.2	6	0.6112	1.1460	0.2368	0.4440	6	2.5	2.3	1
Branch 4	6	4	7	5	3	1	0.5730	0.1910	0.2220	0.0740	2.2	0.2	0.8	0.1
Branch 5	7	3	8	6	1.5	2.7	0.2865	0.5157	0.1110	0.1998	0.4	4.8	0.2	1.9
Branch 6	3	6	4	7	6	3	1.1460	0.5730	0.4440	0.2220	2.6	2.1	1	0.8
Branch 7	4	7	5	8	1	1.5	0.1910	0.2865	0.0740	0.1110	0.2	0.4	0.1	0.1
Branch 8	2	2	9	9	2.5	2.5	0.4775	0.4775	0.1850	0.1850	99.6	24.6	38.6	9.5
Branch 9	9	9	10	10	0.5	0.8	0.0955	0.1528	0.0370	0.0592	16.9	5.7	6.5	2.2
Branch 10	10	10	17	11	3	4.2	0.5730	0.8022	0.2220	0.3108	22.8	19.1	8.8	7.4
Branch 11	17	11	18	12	2.5	1.8	0.4775	0.3438	0.1850	0.1332	14	3.4	5.4	1.3
Branch 12	18	12	19	13	1.1	1	0.2101	0.1910	0.0814	0.0740	3.5	0.4	1.3	0.1
Branch 13	19	1	20	18	4.5	2	0.8595	0.3820	0.3330	0.1480	8.5	13.4	3.3	5.2
Branch 14	20	18	16	19	3	1.1	0.5730	0.2101	0.2220	0.0814	1.4	1	0.6	0.4
Branch 15	16	19	15	20	1.2	4.5	0.2292	0.8595	0.0888	0.3330	0.1	1.5	0	0.6
Branch 16	10	18	11	17	4.2	2.5	0.8022	0.4775	0.3108	0.1850	26.3	3.3	10.2	1.3
Branch 17	11	17	12	16	1.8	2.2	0.3438	0.4202	0.1332	0.1628	5.2	1.4	2	0.5
Branch 18	12	16	13	15	1	1.2	0.1910	0.2292	0.0740	0.0888	0.8	0.2	0.3	0.1
Branch 19	13	15	14	14	1.5	1.5	0.2865	0.2865	0.1110	0.1110	0.1	0.1	0	0
TOTAL											**404.8**	**176.3**	**156.6**	**68.2**

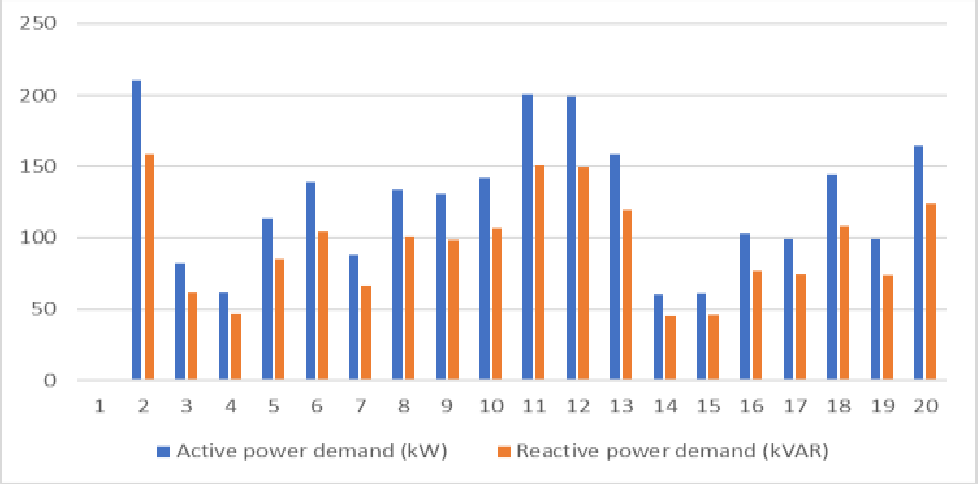

Chart –3 Active and reactive power demand of the mini-grid

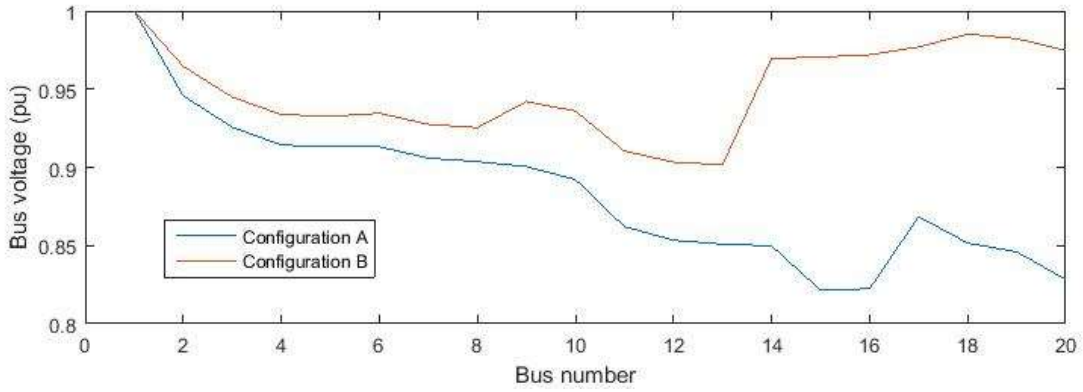

Chart -4 Bus voltage profile of the each configuration

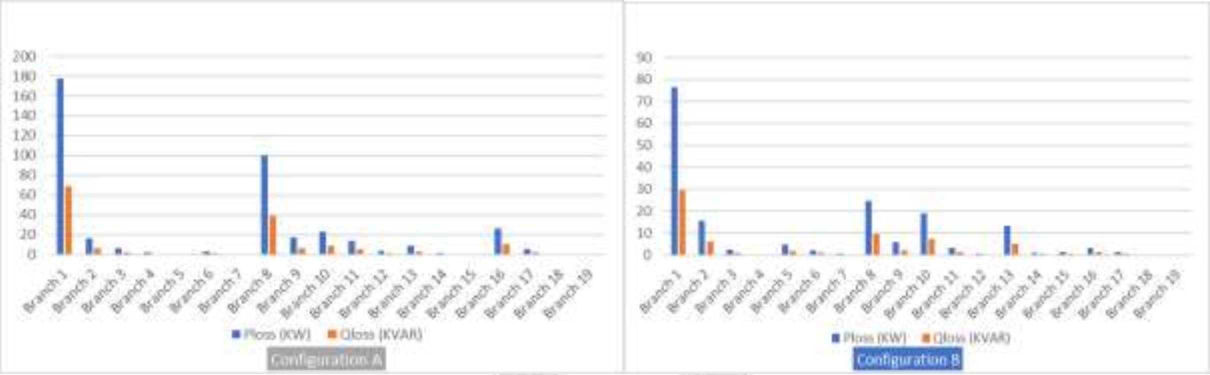

Chart -5 Power losses of each configuration

Common parameters chosen for these configurations:
-Section of line: 120 mm^2 copper cable
-Medium Voltage : 5 kV ; Low Voltage : 220 V
-Power factor : 0.8
-Topology: Radial system with single Synchronous Generator at bus number 1
-Bus selected to form a tie-line in configuration A: 2, 3, 10
-Bus selected to form a tie-line in configuration B: 2, 3, 18

4.3 Discussion

Outputs system data are given in table-3 and table-4. Bus data indicates the bus voltage profile in per unit and in kV; it shows also the power demand in each village and the total power need to generate for supplying loads; whereas line data shows the line impedance (R, X) in each branch according to the distance and line section. Active and reactive power loss in each branch are also observed in the table-4. The total loads (power demand) for the base configuration are 2392.1 kW active and 1793.9 kVAR reactive. The capacity of generator differs for each configuration. As the configuration A, it requires generation of 2796.8 kW because total active loss represents 404.8 kW (16.92%). This loss is reduced to 176.3 kW (6.86%) in the configuration B, so only 2568.3 kW is the power required at the generator-bus. When evaluating these percentages of losses, configuration B is near to the acceptable range but it needs more optimization to attend the power loss threshold considered acceptable (under 6%).
In fact, voltage profile of the configuration A is lower than the usual lower limit of 0.9 p.u (chart-4); it shows that the system is not well configured. It means that a bad choice of a bus to form a tie-line has an impact on voltage profile.

5. CONCLUSION AND PERSPECTIVES

Although assessment of energy needs per village, sizing of power generation in accordance with electrical demand are a difficult assignment; it ensures rural electrification project succeed or fail. This approach is suitable for sustainable energy planning especially for the case of rural isolated areas. It has been proved that sizing an appropriate load corresponding to real data and best selection of mini-grid configuration can improve maximum electrical efficiency both minimizing power losses and maximizing voltage stability in each bus. At each configuration, the one that follow criteria without any constraint violations, is chosen to be a near optimal configuration used for the next step of the full techno-economic optimization.
In this paper, an initial radial configuration of a mini-grid is obtained. It is not the very optimal, it is like a near optimal configuration to serve for further optimization. Future work will be the improvement of this approach to be a new algorithm taking into consideration both branch configuration, generator's placement, appropriate transformer and especially Distributed Generation's placement like single renewable energy system or hybrid system.

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