Assessment on Power Distribution Network Planning in Sub-Saharan Africa

Conference Paper · October 2021

DOI: 10.1109/ICECCME52200.2021.9591074

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Proc. of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)
7-8 October 2021, Mauritius

Assessment on Power Distribution Network Planning in sub-Saharan Africa

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***Abstract*—Power system distribution network planning (PSDNP) encompasses several tasks including ensuring sufficient substation capacity and distribution capacity for the end users. Both rural communities and urban dwellers benefit when there is a well-planned distribution network. City power consumers enjoy stable electricity supply and the number of annually connected rural households increases with an efficient planning scheme in place. However, this is not the case in many cities and rural areas in sub-Saharan Africa. Poor distribution network planning by many power utilities has led to the annual energy demand growing at a much higher rate than the number of electrified households in many sub-Saharan African countries. Therefore, this paper discusses challenges faced by power utilities and energy consumers due to poor distribution planning techniques. This paper proposes an implementation plan to address the inefficient planning challenges faced by the rural communities and urban dwellers. After that, a case study is selected in East Africa, and the solutions are applied.**

Keywords—distribution network, energy demand, planning, stable electricity supply, substation capacity

I. Introduction

Urban areas are ever expanding. Rural and sub-urban areas are also experiencing population growth as birth rates are higher than death rates in villages. With an annual population increase in sub-Saharan African countries comes the rising needs of the people that must be met. Among the cravings of the African population for their welfare and satisfaction is the rising quest for electricity [1]. However, connecting un-electrified households in cities and villages will remain an uphill task if not addressed by efficient distribution planning techniques. More so, frequent power cuts and overloading on electrical infrastructure will result when power utilities do not plan effectively the distribution network [2, 3]. This calls for proper planning of the enlarging distribution networks.

The power distribution system is a complex and important part of the grid which supplies the consumers with electricity via feeders from the electric source [3]. It has a number of components and these distribution equipment should have enough capacity and be well-sized to meet the consumers' peak demands. One main component of the distribution system is the distribution substation. It is the part of the electric power system below the sub-transmission level that transfers power from the transmission system to the distribution system of that area. Distribution substations generally consist of switching equipment, protection equipment like circuit breakers, control equipment, and one or more transformers. Another part of the distribution system are the feeders. After that, we have the customers' connections and meters [3, 4].

The power system distribution network planning (PSDNP) deals with the optimal location of feeders and substations, and sizing of substation distribution equipment such as transformers and feeders to meet current and future load demand for the given time frame [4]. A well-built and well-planned distribution system should be reliable, have availability of power on demand, and allow for minimal losses [5]. To achieve such, distribution equipment be maintained. Preventive maintenance should be conducted after a specific number of years to put in check ageing infrastructures. There could be higher failure rates if distribution system components are not monitored. Added to that, electric loads such as big industrial motors could be started or shut down without prior warning to the power utility. This necessitates that the system must be capable of supplying load demands at any given time. A well-constructed distribution network puts in check the voltage variations. Fluctuations in voltage levels at the end-users point must be minimal and should be within the permissible range of the rated value of the consumer's terminals.. Reliability for a well-constructed system cannot be overemphasized. For improved system reliability, power interruptions should be minimized. If not addressed, poor PSDNP could have negative technical and financial impacts on the power utilities and electricity consumers.

II. Poor Distribution Planning in African Countries

Energy consumers from many developing countries experience a number of interruptions for a number of minutes or hours annually. These interruptions could be unplanned or planned as in times of load shedding [5]. A random selection of some countries with unreliable electricity supply will mostly be sub-Saharan African countries. The information in this section in the paper presents the implications of inefficient PSDNP on utilities and energy consumers in these countries.

A. Unreliable Distribution System

Connected demand points in many cities often lack constant electricity supply mainly due to the (i) system average

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interruption frequency index (SAIFI) below standard, (ii) sub-standard system average interruption duration index (SAIDI), and (iii) customer average interruption duration index (CAIDI) below standard [6].

- *SAIDI*

The system average interruption duration index (SAIDI) is the average time of power interruption for each energy consumer served. It is derived by (1) according to [7];

$$SAIDI = \frac{\sum T_i}{\sum N_i} \quad (1)$$

where T_i is the duration of consumers' interruptions and N_i is the number of power consumers served. SAIDI is measured monthly or annually in minutes or hours.

- *SAIFI*

The system average interruption frequency index (SAIFI) is the number of interruptions per energy consumer. It is calculated as in (2) according to [8];

$$SAIFI = \frac{\sum C_i}{\sum N_i} \quad (2)$$

where C_i is the number of consumers interrupted and N_i is the number of consumers served. SAIFI is measured monthly or annually in number of interruptions per consumer.

- *CAIDI*

The consumer average interruption duration index (CAIDI) is the average service restoration time. CAIDI value is gotten from (3) as in [7, 8]. CAIDI is measured monthly or annually in minutes or hours.

$$CAIDI = \frac{SAIDI}{SAIFI} \quad (3)$$

To ensure power supply continuity to end-users, utilities should opt for a well-planned and reliable distribution network. Utilities use the reliability indices SAIDI, SAIFI and CAIDI to determine how reliable a distribution system is. More so, there are standards set for power utilities to stand by. The median SAIDI value for North American utilities according to the IEEE Standard 1366-1998 is approximately 1.5 hours or 90 minutes. The IEEE Standard 1366-1998 has the median SAIFI value for North American utilities as approximately 1.10 interruptions per energy consumer. According to the IEEE Standard 1366-1998, the median CAIDI value for North American utilities is approximately 1.36 hours or 81.6 minutes [8]. Unfortunately, the reliability indices for many sub-Saharan African countries are below standard as compared to the IEEE standard. With inefficient planning by distribution planners, such sub-standard SAIDI, SAIFI and CAIDI indices result and power consumers experience frequent power interruptions. Table I shows the reliability indices of some African countries. While the standards for reliability indices are in the range of 1.0 and 2.0, some African countries have SAIFI and SAIDI indices higher than 50 as seen in Table I. This is as a result of inefficient planning of the distribution network.

TABLE I. COUNTRIES AND THEIR RELIABILITY INDICES [9]

Country	SAIDI (in hours)	SAIFI (interruptions per consumer)
Tanzania	60.4	61.9
Botswana	32.4	49.2
Nigeria	139.2	393.6
South Africa	44.0	6.5
Zambia	176.0	17.9
Zimbabwe	243.6	21.7

B. *Increased Power Losses*

Many power utilities in sub-Saharan African countries experience power losses high above the allowable range. Improper sizing of feeders, high energy demand and poorly maintained networks result in such high losses along distribution lines. Unbalanced allocation of distribution feeders and long end-user distance from distribution transformer increase the losses in a distribution line. More so, unplanned distribution lines' extensions and overloading of distribution components like transformers and feeders result in high losses and the feeders getting overheated [10]. According to [11], electric system losses should range between 3% and 6%, however many sub-Saharan African countries suffer from power distribution losses of about 20%. Utilities encounter technical setbacks of unreasonably high line losses when the PSDNP is poor. Distribution line losses can be calculated as in (4), (5) and (6) according to [12].

$$P_{ab} = V_a[V_a G_{ab} - V_b(G_{ab}\cos\delta_{ab} + B_{ab}\sin\delta_{ab})] \quad (4)$$

$$Q_{ab} = V_a[V_a(-B_{ab}) - V_b(G_{ab}\sin\delta_{ab} - B_{ab}\cos\delta_{ab})] \quad (5)$$

$$\delta_{ab} = \delta_a - \delta_b \quad (6)$$

where P_{ab} and Q_{ab} are the real and reactive power from node a to node b respectively, δ_a and δ_b are the angles at nodes a and b respectively, δ_{ab} is the angle between the two node voltage vectors, V_a and V_b are the voltages at nodes a and b respectively, G_{ab} and B_{ab} are the distribution's line admittance and suseptance respectively.

C. *Low Benefit-Cost Ratio to Utility*

Operation conditions vary continuously as new customers are connected to the distribution network, prices grow, weather conditions change, and distribution equipment approach the end of their finite life. This necessitates the importance of estimating future conditions [13]. Since predictions may not be exact, uncertain factors should be considered. Added to that, sufficient time and huge investments are required for a properly planned distribution network. This means that poor planning mistakes by the distribution planners could result into huge financial losses.

Utilities in many sub-Saharan African countries are often are challenged by low benefit-cost ratios due to poor PSDNP. Power utilities use the benefit-cost (B_C) ratio to determine the feasibility of supplying electricity via a particular distribution network to a particular area. The ratio is derived as in (7) according to [14];

$$B_C = \frac{I_C}{N_C} \quad (7)$$

where N_C and I_C are the number of connected power consumers and the investment cost to power that area respectively.

D. Low Electrification Rates

The power generation capacity might be sufficient for the targeted population, but poor PSDNP by planners could leave a considerable percentage of the population un-electrified. Urban electricity access rates and rural electrification rates are impacted by the executed planning scheme, be it beneficial or not. Table II shows the electricity access rates and rural electrification rates of some African countries as at 2019.

TABLE II. COUNTRIES AND THEIR ELECTRIFICATION RATES [10, 14]

Country	Country Electricity Access Rate (%)	Rural Electrification Rate (%)
Tanzania	35.6	24.5
Botswana	64.9	9.0
Nigeria	56.5	39.0
South Africa	91.2	50.0
Zambia	39.8	3.0
Zimbabwe	41.0	8.0

III. METHODOLOGY AND MODEL

A. Methodology for Urban Distribution Network Planning

Different options for planning by utilities include implementation of demand response programs, plug-in electric vehicles usage by smart discharging or charging, insertion of distributed generation resource such as nonrenewable and renewable energy sources, energy storage system installation, and network reconfiguration [15]. This paper proposes network configuration as a feasible method for PSDNP in sub-Saharan African countries. Fig. 1 shows the flowchart for the proposed planning scheme for urban areas.

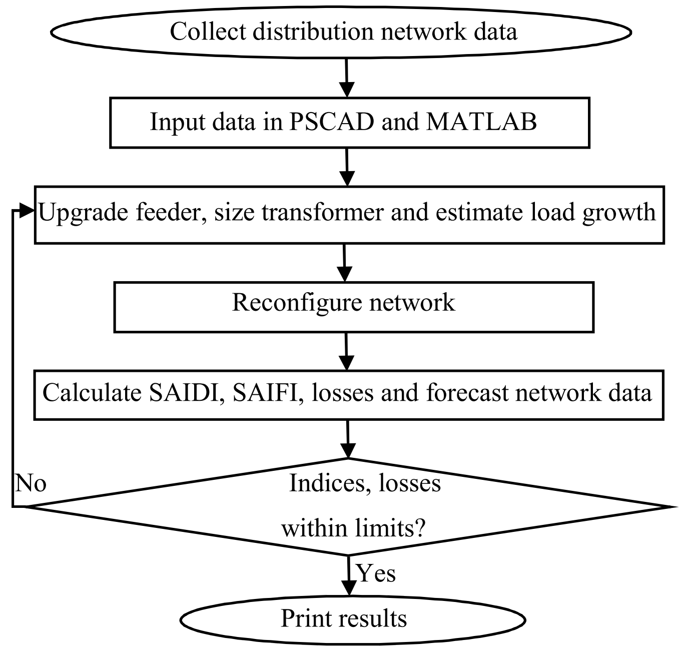

Fig. 1. Flowchart for proposed planning scheme

B. Model for Distribution Network Expansion to Rural Areas

Electrification rates, high power losses and low benefit cost ratio to utilities could be improved by proper planning techniques that allows for expansion of the distribution network for future loads especially in the rural and sub-urban sector. This paper models a feasible planning and expansion technique of the distribution network. This cost-effective grid extension model is the single wire earth return (SWER) system [14] as seen in Fig. 2. The SWER system is composed of a number of parts [11, 13]: (i) 11 kV/6.35 kV isolation transformer; (ii) aluminium conductor steel reinforced (ACSR) conductor; (iii) pole support; (iv) 6.35 kV/230 V distribution transformer; (v) protection system using fuses and circuit breakers; and (vi) earthing system. SWER aids in minimal-cost addition of distribution lines for future rural and sub-urban consumers, as well as, improving technical losses along lines and the benefit-cost ratio to utilities.

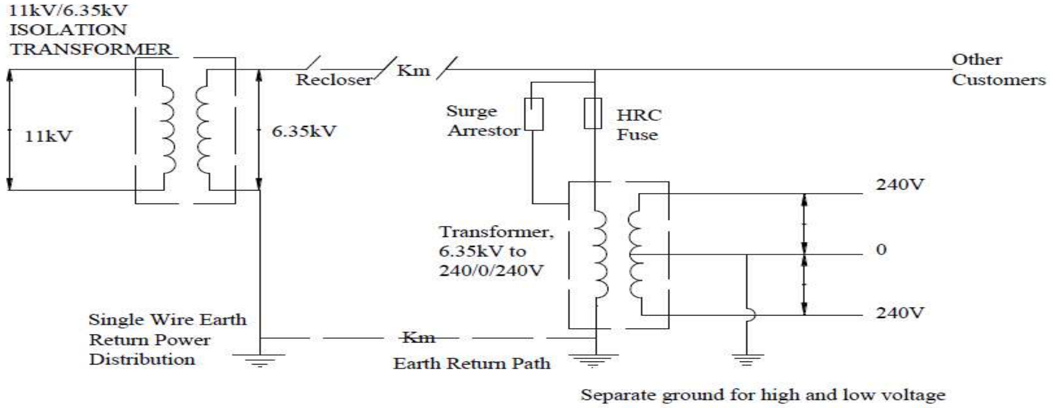

Fig. 2. SWER model showing isolation and distribution transformers, and earth return path

IV. APPLICATION

A. Case Study in East Africa

Up to this point, the authors have discussed the challenges faced by the poor planning of the power distribution sector in sub-Saharan African countries and the negative impacts such could have on the energy consumers and the utilities. It was shown that without proper distribution network planning, utilities will yet suffer from more power losses and electricity consumers will still experience frequent power cuts. Added to that, the limited technical know-how on PSDNP will further rise the trend on un-electrification rate in the region. To avoid emergency planning, partaking in planning under normal conditions is advised because it is beneficial [4, 14]. Therefore, this section chooses Tanzania as the model country and applies the city planning flowchart in Fig. 1 for a Dar es Salaam city regional distribution network, and the SWER model in Fig. 2 for extension planning of the distribution network to Homboza village in Tanzania. Dar es Salaam city located in the eastern part of Tanzania lies along the coordinates 6.7924 °S, 39.2083 °E and is divided into five districts which are Kinondoni, Ilala, Ubungo, Temeke, and Kigamboni. Homboza village located in one of the Coast regions in Tanzania has coordinates 7.3238 °S, 38.8205 °E with 171 households. Dar es Salaam city and Homboza village were selected to impart benefits of proper PSDNP to other cities and rural areas respectively.

B. Results and Discussion

The information in this section in the paper presents the benefits of the Fig.1 flowchart and the Fig. 2 model in Dar es Salaam city and Homboza village respectively.

1) Reliability level: Data was collected from a sample regional distribution network in Dar es Salaam after being subjected to test by the proposed method. The sample network contains five feeders and is fed from a 33 kV/11 kV transformer. The regional distribution network was studied and results from analysis and calculations are presented in Table III and Table IV. The regional distribution system was studied over the month of January. The total number of interruption minutes that consumers experienced were recorded as can be seen in Table IV. Also, the total number of energy consumers that experienced interruptions during that month were recorded. The Energy and Water Utilities Regulatory Authority (EWURA) in Tanzania set standard reliability indices for the power utility to adhere to. The Tanzanian power utility company, Tanzania Electric Supply Company Limited (TANESCO) ought to abide by the set standards, though compliance has been an uphill task. According to the Tanzania Standard TZS 1374:2011, Section 7, the SAIDI should not exceed 10.8 hours or 648 minutes, the SAIFI should be less than 3 interruptions per consumer, and the CAIDI should not be more than 3.6 hours or 216 minutes [6]. From Table III, the total number of consumers are 5,249. There was a total number of 8,720 customers that experienced outages and consumers' outage duration of 2,311,360 minutes as shown in Table IV. Therefore, from (1), the SAIDI value is approximately 440 minutes. The SAIFI value is 1.66 interruptions according to (2). CAIDI derived from (3) is approximately 265 minutes. Fig. 3 shows the improved reliability indices after proper PSDNP as per the IEEE and the EWURA standards.

TABLE III. REGIONAL DISTRIBUTION SYSTEM IN DAR ES SALAAM

Feeder	Number of Consumers Served
Feeder 1	2,500
Feeder 2	1,700
Feeder 3	323
Feeder 4	720
Feeder 5	6
Total	**5,249**

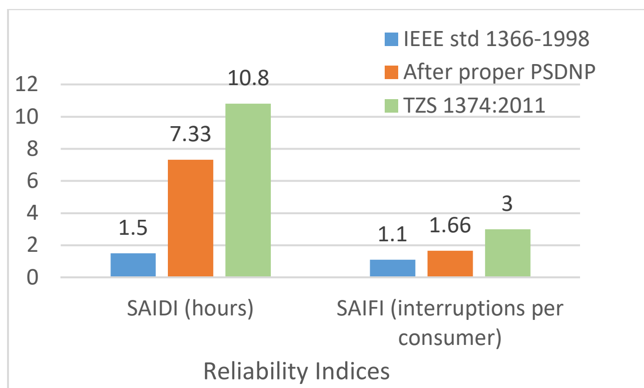

Fig. 3. Reliability indices between distribution system and set standards

TABLE IV. REGIONAL DISTRIBUTION NETWORK OVER THE MONTH OF JANUARY

Feeder	Date	Outage Period		Outage Duration (minutes)	Number of Consumers that Experienced Outages	Consumers' Outage Duration (Minutes)
		Out	In			
Feeder 1	1st January	12:00	12:05	5	2,500	12,500
Feeder 5	1st January	13:00	15:10	130	1,300	169,000
Feeder 2	3rd January	06:09	13:50	461	1,700	783,700
Feeder 4	13th January	18:00	21:23	203	720	146,160
Feeder 1	30th January	09:00	17:00	480	2,500	1,200,000
Total					**8,720**	**2,311,360**

2) Power distribution losses: EWURA limits the power distribution losses in accordance with ESI-RSR, 2014 Section 6.2 to 6.4 for TANESCO to 12%. However, TANESCO's distribution losses stood at 14.5% as at June 2020 [6]. The utility's failure to comply with the set standard is due to poor PSDNP schemes. This section applies the proposed model to the regional distribution network. After configuration, the active losses came to 10.8% according to (4). This is shown in Fig. 4.

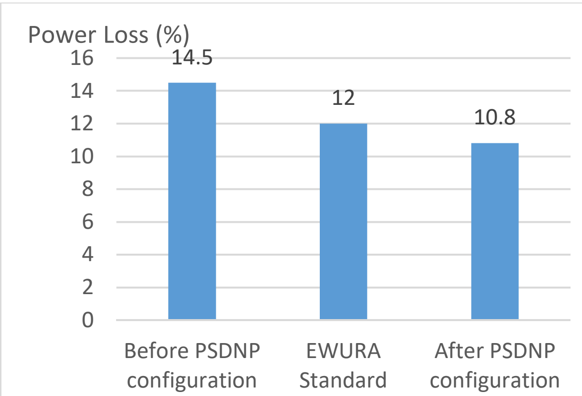

Fig. 4. Power distribution losses before and after PSDNP

3) Benefit Cost Ratio to Utility: To improve the benefit-cost ratio to TANESCO, the proposed planning model encompassing on-grid extension using SWER to rural and sub-urban areas was applied to Homboza village. Applying SWER is cost-effective to TANESCO in supplying the Homboza village households with electricity as can be seen in Table V. Homboza village has 171 households according to data gotten from the village chairman. The electricty supply costs in Table V is shared for the 171 households.

TABLE V. COSTS FOR SUPPLYING HOMBOZA VILLAGE BEFORE AND AFTER PROPER PSDNP (IN TSH)

Material	Before PSDNP SWER configuration	After PSDNP SWER configuration
Pole	107,040,000	66,915,000
Distribution transformer	21,797,000	21,797,000
ACSR	31,560,000	15,800,000
Pole-top assembly	13,640,000	5,040,000
Earth connectors	0.0	240,000
Total	**174,037,000**	**109,792,000**

According to (7), N_C is 171, the I_C before the PSDNP SWER configuration is 174,037,000 Tsh and the I_C after the PSDNP SWER configuration is 109,792,000 Tsh. Therefore, the B_C ratio to the utility TANESCO improves by about 36.8% and this is shown in Fig. 5.

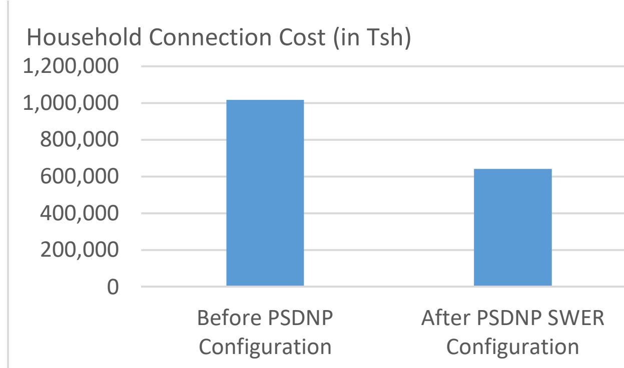

Fig. 5. Homboza village household connection costs before and after PSDNP

4) Electricity Access Rate: Despite having sufficient installed generation capacity, the electricity access rate of Tanzania stood at 35.6% and the rural electrification rate at 24.5% as at 2019 [10, 14]. This is due to poor PSDNP. Electrification rates in both rural and urban areas are affected positively when the PSDNP scheme is efficient. This results in the increase of average annual household connections. While solving the electrical energy challenges facing the urban dwellers in Dar es Salaam, the Homboza villagers should not be left out. By applying the PSDNP scheme of on-grid extension using SWER to rural and sub-urban areas, the Homboza village dwellers will enjoy electricity supply and Tanzania's connection rates will improve. Knowing the estimated load is beneficial in PSDNP [16]. The estimated load demand for the 171 Homboza households was calculated and the daily curve is shown in Fig. 6. Having known the peak Homboza load, possible size of distribution transfomer for the Homboza load can be estimated as shown in Table VI.

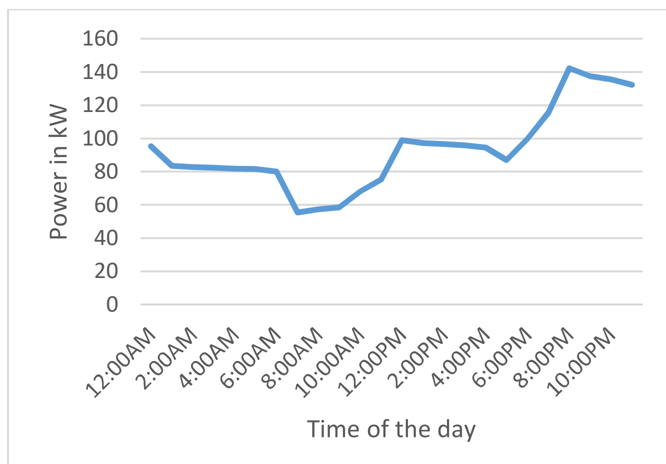

Fig. 6. Homboza Village Daily load demand curve

TABLE VI. LOAD ESTIMATION AND TRANSFORMER SIZING

Total Peak Load	Power Factor	Peak Apparent Power	Product Factor	Transformer Rating
142.3 kW	0.91	156.37 kVA	1.28	200 kVA

With the PSDNP SWER technique, electrification rates of rural and sub-urban areas could increase by about 36.8% according to (7). Since the saved investment cost could be used by TANESCO to connect more households, more Homboza inhabitants get to benefit electricity supply as shown in Fig. 7.

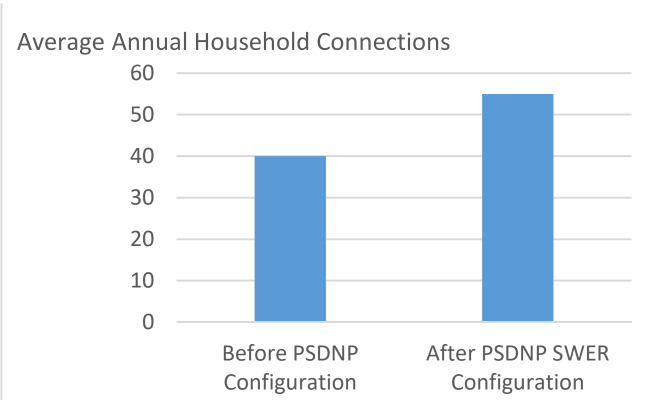

Fig. 7. Homboza village household connections before and after PSDNP

V. Conclusion

This paper assessed the impacts of poor PSDNP on power utilities and energy consumers. It was shown that proper PSDNP strengthens the rural electrification initiative in Tanzania and brings about a number of other benefits to the power end-users and the utility including improved power losses and a more reliable system. Distribution planners should be led to cost-effectively implement the proper distribution planning scheme for the city of Dar es Salaam, the electrification of Homboza village and by extension, other fast-growing sub-Saharan African cities, rural areas and regions.

Acknowledgment

Appreciation goes to the Magomeni distribution division under TANESCO for the completion of this research. Sincere thanks to EWURA for helping with data collection.

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