RURAL ELECTRICITY DISTRIBUTION SYSTEMS IN GHANA: ANALYSIS AND VERIFICATION OF SELECTED DESIGN FACTORS

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ABSTRACT

Rural electrification is a strategic component of economic development in Ghana. Its execution has led to rapid growth in sub-transmission line extensions and installation of new transformers, with problems that require analysis. Issues related to the sizing of transformers and line extensions are dealt with here. In particular the degree of penetration of appliances and energy consumption have been used to forecast loads for sizing of transformers. Other issues such as high voltage drops and voltage imbalance have been considered. Data obtained from measurements in three towns were used to verify load factors normally assumed in distribution network design. The parameters of the 33-kV line serving Bekwai from Kumasi were used to analyse voltage drops and voltage regulation, and to determine additional line extensibility and loadability based on the MVA.km as a transmission factor.

Keywords: *Rural electrification, voltage regulation, load factor, load estimation, switched capacitors.*

INTRODUCTION

Electricity is a major factor of modern industrial and economic growth. In recognition of this the National Electrification Scheme (NES), was instituted to provide the framework for supply of electricity to towns and villages by the year 2020. A key component of this scheme was the plan to provide electricity to all district capitals in Ghana. A second component was the supply of electricity to all towns and villages situated within 20 km of the 11-kV and 33-kV sub-transmission network. This was to be supported by the provision of poles by the communities involved themselves. This programme is known as the Self Help Electrification Project (SHEP). This has so far attracted over 2000 communities in the country. The demand for electricity on the above scale requires an expansion of the transmission network including the number of substations all over the country. Until recently the available generation rated at 1020MW was hydropower based. However, the very low rainfall recorded in the catchment areas of the hydro reservoirs has changed for good, the generation plans for the future. The previous large reserve margins no longer exist. There is pressure on the generation system. Load shedding has been widely resorted to in the face of inadequate inflows into the Volta Lake, with serious consequences for industry. In spite of this, the rural electrification programmes are on course, at least to put the required networks in place.

In this paper some of the current practices in the analysis and design of rural electrification schemes are reviewed. The objective is to verify parameters that determine the quality of supply of power based on voltage regulation, total system losses and voltage imbalance [1]. These are serious problem areas particularly because the distribution systems are largely radial in nature. The radial nature is not restricted only to the rural areas but are also common in the urban areas. The main difference is that there are more circuits in the urban areas. Data from two districts in Ashanti Region, namely, Amansie East with capital at Bekwai and Bosomtwe-Atwima-Kwanwoma with capital at Kuntanase, will be used as typical examples. The sub-transmission system from Kumasi to Bekwai in the Amansie East District and some of the towns along that line has been used in this work. Loads from three other rural towns were measured and analyzed to verify some of the design concepts and assumptions. The results should be applicable to most areas of the country with little if any modification.

LOAD ESTIMATION

The major factor in the supply of electricity to any town is the size of load leading to the determination of transformer size for the area.

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An under estimation leads to brown-outs or transformer overload and burn-out, while over estimation leads to high capital expenditure and under utilisation of the transformer.

The load estimates, in the absence of historical loads in a new area, depend on the following factors and assumptions; present population of the town, average population growth rate, present number of households, average number of persons per household, estimated residential load factors, estimated non-residential load factor, initial penetration factor, final penetration factor, non-residential coincidence factor, spot loads such as corn mills and hospitals, and average power factor. The loads will be classified as either residential, non-residential or commercial and spot loads. The basic data for load estimation is obtained from field surveys. All households in the towns or villages are considered. These include households that could be wired for supply at the time of the initial survey, as well as those dilapidated houses that may be rehabilitated and wired up later.

A total of 185 towns were assessed in this study for electricity supply in the Amansie East and Bosomtwe-Atwima-Kwanwoma districts.

Equation (1) was derived to estimate load in kilowatts for each community.

$$P = NHH \times ACHH \times PF \times DF / LF \times 8760 + SL \quad (1)$$

where

NHH is the number of households in the community at the end of a 10-year projection of the population from a specified base year.

ACHH is the average consumption per household in kWh/year

PF is the electricity penetration factor as fraction of houses that will be connected.

LF is the load factor.

DF is the diversity factor

SL represents spot load kW

FIELD SURVEY

In the field survey the total resident population of adults and children is obtained. Most village unit committees keep records of population figures. The number of residential households is counted. An estimate of the average number of persons per household is made. A layout of the town is drawn or obtained for the siting and installation of transformers and lines. Notes of any obstacles such as high hills or rivers are also made. National demographic data is sought to determine the rate of population growth for the area. The average population growth rate is a critical factor used to forecast the user population over a 10-year period from the base or commissioning year. This is critically important to ensure correct sizing of the transformer for the community.

ANNUAL LOAD FACTOR

The annual load factor is the ratio of average power over the year to the peak power in that year [2]. These are easily found from load curves where they exist. However for a town yet to be supplied with electricity the load factor can only be estimated from general energy use data for towns or villages of similar size. In most towns and villages, farming is the main activity and the communities are virtually deserted until late afternoon and evening. There is thus a very wide variation between average power and the peak power for the day which occurs in the early evening hours. The transformer must be rated to supply the peak load over about a two to four hour period from sunset to about 10.00 pm. This is mainly because the load in the small communities is predominantly for lighting and light entertainment. The major end use elements at this time are lights, music systems, radios, fans and small refrigerators. Others include immersion heaters and electric irons. Data on energy usage by the above elements were obtained out of a study on "Projected Average Residential Electricity Use" commissioned by the National Energy Board (NEB) in 1992.

LOAD FACTOR ESTIMATION

Table 1 was used to derive reasonable estimates of the daily load factor.

Table 1: Domestic appliance ratings and use. Data for villages with population less than 2000

	Consumption kWh/mon.	Penetration Rate %	Average Hours of Usage	kWh/yr Household
Lights	48.6	100	6.75 hours per day	583.2
Music	7.2	50	6 hours per day	43.2
Radio	0.72	76	6 hours per day	6.6
Electric iron	16.0	51	5 hours per week	97.3
Immersion Heater	2.5	45	50 times per month	13.5
Electric Fan	18.0	40	8hr. per day, 1.5 per household	87.1
Fridge	100.0	6	12 hours per day	72.0
Miscellaneous	75.0	0.5	Low penetration	16.5
Total				919.4

Table 2: End Use Peak Loads Per Household

	Peak load per household in watts	Percentage of total watts
Lights	240	74.77
Music	20	6.23
Radio	3	0.93
Electric Fan	40	12.46
Refrigerator	8	2.49
Television	10	3.12
Total	321	100

Table 3: Sample data collected

Time of day	Phase to Neutral volts	Percent voltage	Line 1 Current Amps	Line 2 Current Amps	Average current Amps	Percent Current Imbalance	Percent Transformer loading	Total Power kW	Total Energy kWh	Average Power Factor
12.00 pm	236.50	98.54	11.05	16.73	13.89	20.45	11.80	5.90	2.50	1.000
12.15 pm	238.89	99.54	14.88	10.41	12.65	17.67	10.56	5.28	3.80	1.000
12.30 pm	241.80	100.75	11.08	10.02	10.55	15.02	8.84	4.12	4.89	0.932
12.45 pm	241.19	100.50	10.94	15.46	13.20	17.12	11.30	5.65	6.22	1.000
01.00 pm	243.10	101.29	11.16	9.19	10.18	9.68	8.56	4.02	7.36	0.939
01.15 pm	241.60	100.67	11.13	9.94	1054	5.65	8.82	4.10	8.38	0.930
01.30 pm	240.19	100.08	12.89	14.58	13.74	6.15	11.43	5.62	9.48	0.983
01.45 pm	240.89	100.37	14.36	10.60	12.48	15.06	10.40	5.03	10.66	0.967
02.00 pm	243.40	101.42	12.82	10.74	11.78	8.83	9.94	4.65	12.04	0.936
02.15 pm	243.80	101.58	12.83	10.39	11.61	10.51	9.82	4.63	13.21	0.943
02.30 pm	244.30	101.79	16.51	14.44	15.48	6.69	13.62	6.81	14.63	1.000

Hitherto, load factor estimates have been mostly difficult to support. The Table shows in the totals row that the average annual energy consumption in a typical village with a population not exceeding 2000 is about 920-kWhs. This is equivalent to an annualised average power per household of 105 watts.

From the Table above the total peak load per household per end use can be found from the following simple relationship derived by the author in equation 2.

$$P_{max} = \sum_{i=1}^{n} \frac{E_i \times 1000}{H_i \times R_i} \qquad (2)$$

where

E_i is the energy in kWh consumed per month by each end use

H_i is the number of hours of use per month of each end use

R_i is the penetration rate or factor of each end use

n is the total number of end uses

The results of the calculations are shown in Table 2

The estimated peak load per household from the data is thus 321-W. Average contributions from other end uses such as immersion heaters, electric irons and electric cookers, are not appreciable during the peak load periods which are between the hours of 6-10 p.m. The system load factor [3] is thus found by calculation using equation 3.

$$LF = \frac{P_{ave}}{P_{max}} \qquad (3)$$

From the ratio of 105 watts to 321 watts the load factor per household is 0.327. This load factor was used as a capacity factor in transformer sizing. In other words this is equivalent to the load-to-transformer capacity ratio in the commission year. It is necessary to determine a realistic load factor for general application. One way is to use data from similar towns that have recently been electrified. Another approach is to use recorded average energy consumption data to calculate an average load factor as has been demonstrated above.

Data Collection

Measurements of power, energy and power factor, voltage and current were made at the transformer secondaries in selected towns supplied with electricity within the past two years. Measurements were made using a Prowatt 3 Energy Analyser programmed as a data logger. Recordings were made over 24-hour periods and the recorded data was downloaded into a spreadsheet for analysis. A representative sample of the data collected is presented in Table 3, which shows line-neutral voltages and total power, energy, calculated percentage current imbalance and loading.

Figure 1 shows a 24-hour data segment for line-neutral voltage and total power consumed by one of the communities during the test period.

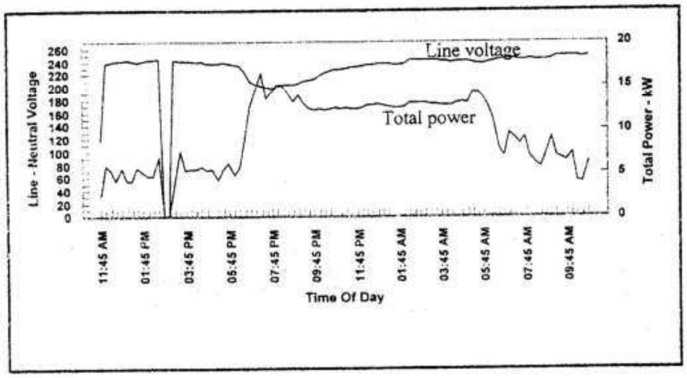

Figure 1: Line neutral voltage and total power

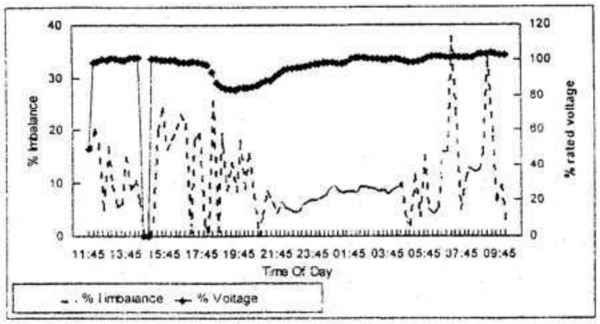

Figure 2: Plot of percentage current imbalance, voltage and loading.

Table 4: Energy use data from newly supplied towns

Name of Town	No. of households connected	Total kWh/day	kWh per household per day	kWh per household per month	kWh per household per year
Yabi	46	227	4.95	148.5	1807
Akyeremade	44	220	5	150.0	1825
Behenase	42	210	5.03	150.9	1836

The measured currents also showed a current imbalance varying from 10 to 25%. This level of imbalance is unacceptable for the proper operation of distribution systems [3, 4] as it usually leads to unacceptable voltage imbalances in high tension networks and is detrimental to the proper operation of large industrial rotating machinery. It is observed that the current imbalance tracked the power curve, an indication of the unbalanced power loading on the transformer. Figure 2 further shows that the voltage level is worst when current imbalance is highest. There are two main causes of current imbalance in our distribution systems. One cause is from improper distribution of loads on the three phases. The second is from load shifting by single phase consumers supplied with 3 phases. Corrections in load balancing will be necessary to improve voltage supply to support light industrial activities and to reduce system losses.

TRANSFORMER LOADING FACTORS

The total energy measured at the end of the 24-hour period in Akyeremade, one of the villages considered, averaged 220kWhs. The installed transformer rated capacity is 50-kVA, single phase, 11kV/230-0-230 volts.

The total number of connected households in this reference community was 44, yielding 5 kWhs per day household or 150 kWh per month household or 1825 kWh per year per household. Measurements were made in 2 additional towns, and covering several days. The results are summarised in Table 4.

The energy per day is almost constant, varying by the length of outage periods. From Figure 1 the load factor is estimated to be 0.56. This is an indication that the average power is much higher than originally estimated. This implies that loads stay on longer, such as will be found in the use of refrigerators and freezers. Interviews of users in the communities revealed that 10% of the connected households were operating deep freezers for ice water sales. Another 10-15% also had refrigerators. This shows a higher penetration rate than Table 1 indicates, contributing to the higher load factor. From Figure 1 the following calculations and inferences were made:-

Average total load over measured period	= 9.6 kW
Peak load	=17.0 kW
Transformer capacity	=50.0 kW
Calculated load factor	= 0.56
Calculated peak load to transformer capacity ratio	= 0.34

The estimated load factor from the load curve is 0.56 as explained above. However it was found out that the ratio of measured peak load to transformer rated capacity is 0.34, almost identical to the theoretical load factor of 0.33 estimated using Table 2. This gives a measure of confidence in the data used for the determination of transformer capacity.

SUB-TRANSMISSION SYSTEM VOLTAGE DROPS

Line voltage drop

Voltage drop is a serious and widespread problem in Ghana in sub-transmission and distribution networks. The consumer-end nominal voltage is invariably very low, particularly in the rural areas supplied on relatively long circuits. The effect on industry and water pumping stations is well known, leading to stoppage of production due to very low receiving-end voltage. The 11 and 33-kV sub-transmission lines that emanate from substations in large towns and cities are mostly radial and relatively long. The NEP and SHEP electrification programmes of the Government have the effect of increasing the loads on these lines while at the same time extending them in order to reach more communities. The capability of a given line for extension is constrained by the voltage drop on that line. It also depends on the loading and type of system: three phase or single phase.

The approximate voltage drop, VD, in a specified section of line is given by:

$$VD = 3 \times S \times \frac{(R \times COS\phi + X \times SIN\phi) \times d}{1000 \times p \times kV^2} \text{ per unit} \quad (4)$$

with nominal voltage as base voltage and

$S = \xi P + j(Q - Q_c)\,\xi$,

where P is the load kW,

Q the load kVAr,

Qc the shunt capacitance at the load point,

ϕ is the power factor angle at the load point,

kV is the nominal line-to-line voltage,

S is the load point kVA

p is the number of phases and

d is the distance in meters of line section

Some communities under the NEP and SHEP programmes are supplied single phase. In the expression for voltage drop twice the distance, d must be used for accuracy. It is to be noted that for the same power transmitted the ratio of voltage drop in a single-phase circuit to that in the same length of a three-phase circuit is 6 [5]. This largely explains the complaints of low voltage, which is prevalent in communities supplied with single phase. A possible solution is to use capacitors for voltage improvement or preferably to adopt the use of larger conductors, such as 150mm² aluminium conductor in single-phase circuits.

Voltage levels are required to conform to some acceptable standards as shown in Table 5. However, more often than not these limits are not met. At the design stage it is necessary that voltage drops are calculated. A voltage drop factor may be determined from equation 4 to assist in the easy layout of voltage drop calculation [6].

Using equation 4 the voltage at a distance from the source point can be calculated. Figure 3 shows voltages at load points on a 50-km, 33-kV line constructed with 100mm² aluminium conductor.

The voltage at the end of the line at peak load is 29.3 kV or a voltage drop of 10.6% of the sending end voltage. This is lower than the allowable minimum as shown in Table 5. Further increases in load will dramatically depress the voltage.

Under the SHEP programme 11-kV and 33-kV sub-transmission lines are being extended to supply electricity to more remote areas. This places heavier demands on the existing lines in terms of voltage regulation and thermal limitation.

Table 5: Utility line voltage limits [E.C.G. System Operating Limits]

	LV	MV	HV
	Volts	kV	KV
Nominal	238/412	11	33
Minimum	207/358	11.25	29.98
Maximum	253/438	11.69	36
Emergency	185/323	10.26	26.44

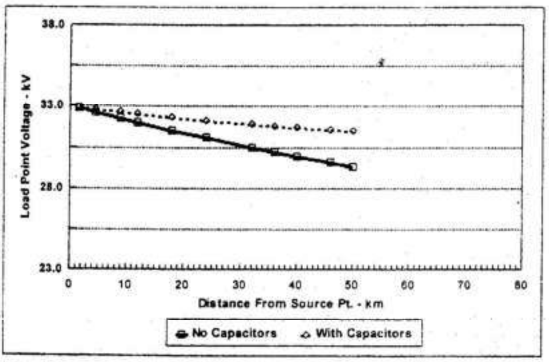

Figure 3: Line voltage at Load Point. 2200 – kVAr Capacitance Bank Used

One of the commonest complaints in the rural areas is that of low voltage usually described as "low current". It is to be noted that corresponding to the voltage drops seen in Figure 3, consumer level voltages as low as 170-volts were recorded between the peak load hours of 7.00 to 9.30 pm. Incandescent lamps dim and fluorescent lamps cycle off and will not restart. The off-peak hours lasting about 17.5 hours generally showed acceptable levels of voltage. The load curve in Figure 1 further showed that the total community load drops off to below 50% of the off-peak period loads.

The method of voltage regulation in the areas studied was by the use of transformers fitted with manually operated off-load tap changers. A high set secondary voltage produces very high no-load voltages on the line, while a low set point results in very low peak period voltages. The load profiles of our towns and even most of our industrial loads require the adoption by the distribution utilities of automatic voltage control methods, such as automatic tap changers, voltage regulators or switched shunt capacitor banks.

SUB-TRANSMISSION LINE EXTENSION

Under the SHEP programme, towns within a 20-km radius of an existing sub-transmission 11 or 33 kV line may be eligible to be considered for supply of electricity. These towns, in time, become future source points for other towns. It is therefore necessary to determine:-

1. the additional incremental load that can be picked up on the line,
2. the additional extension of the line in km to other communities,

or a combination with the above.

Voltage drop is the most appropriate criterion limiting the additional load and extension of the line. Line loss as a criterion is a less stringent constraint from the consumer supply point of view as can be seen in Figure 4. For the test line, the line loss at full load is within an internationally acceptable value of 3% for sub-transmission lines.

It is useful to have a characteristic that can be used to answer the question of additional load and line extensibility. Such a characteristic is shown in Figure 5, a plot of MVA.km and percentage voltage drop versus distance from the source point. The objective for connection of service is best served by the voltage drop limitation.

This composite Figure provides an easy tool to determine satisfactory answers to the above two questions. The MVA.km has both loadability and extensibility functions. The example under consideration shows a line that is overloaded as determined by a voltage drop of over 11% at the end of the line. In this case shunt capacitors have been applied at the end of the line in order to bring the voltage drop within ECG's 9%

specification in 33-kV networks. Curves 1 and 3 show percentage voltage drop and MVA.km along the line with no shunt capacitors installed on the line. The maximum voltage drop is 11%, while the maximum MVA.km is 235.Curves 2 and 4 repeat the above but this time with shunt capacitance of 2200-kVAr at the end of the line. The voltage drop reduces to 4.2%, while there is a release of over 75-MVA.km for increased loading or extension. In this example, for a 20-km extension the total distance from source will be 70-km and the maximum uncompensated load that can be picked up will be approximately 1.07-MVA at which the voltage drop will increase back to 11%. Suppose the load at the end of the line is to be increased without extending the line then the additional load is the quotient of 75-MVA.km and 50-km or 3.75-MVA. As shown in Figure 6 the maximum possible compensation need not be applied to the line. Incremental banks can be added as the load increases and as it becomes necessary to extend the line.

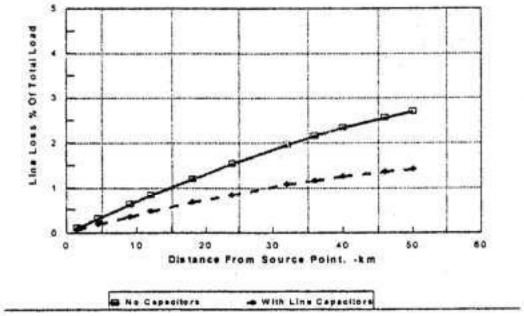

Figure 4: Cumulative line loss versus distance. 2200-kVAr capacitance used.

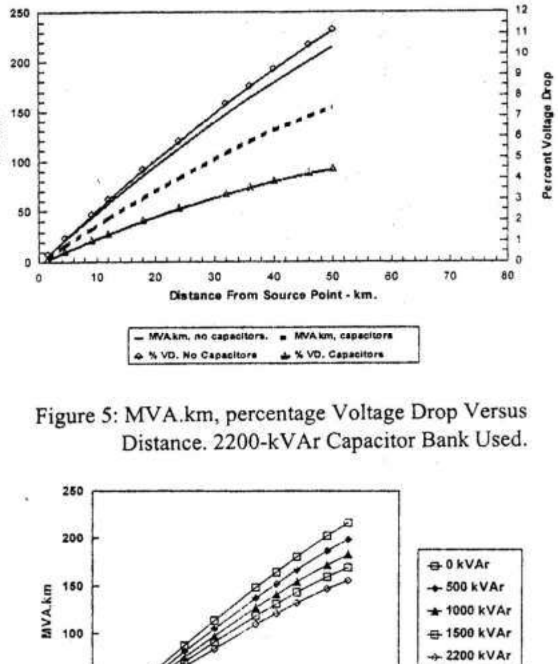

Figure 5: MVA.km, percentage Voltage Drop Versus Distance. 2200-kVAr Capacitor Bank Used.

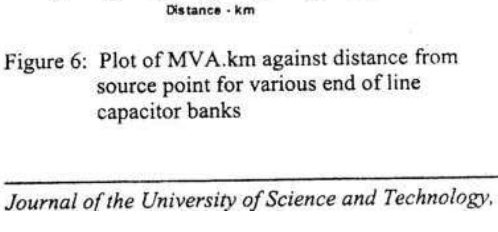

Figure 6: Plot of MVA.km against distance from source point for various end of line capacitor banks

CONCLUSION

Appliance penetration and energy consumption tables were used to obtain supportable estimates of load factor for transformer sizing in rural distribution systems. This can also be approximated by the measured peak load to transformer capacity ratio in the initial years after installation. The actual measured load factor on the transformer is however quickly modified by the early commercial activities adopted by consumers.

Load imbalance which is often left unattended to, may be the cause of several low voltage problems. It is very simply corrected by load balancing. The practice where single phase premises are serviced with 3-phase supply needs to be discouraged.

Line voltage drops and voltage regulation are high and unacceptable. The utilities should consider the use of switched capacitor banks and or percentage voltage regulators or transformers fitted with automatic tap changing under load (TCUL) devices. For simplicity and maintainability switched capacitor banks are recommended.

Single phase sub-transmission circuits should be used sparingly in view of the high relative voltage drops for the same power transmitted when compared to 3-phase systems. The use of 50mm² aluminium conductors in distribution networks should be reconsidered for a large conductor size such as 100mm² or 120mm² in view of the much higher transformer secondary currents carried.

Finally it has been shown that by the use of MVA.km versus distance plots, questions about how much additional load can be carried by a given circuit and how long the circuit may be extended are easily answered. These are crucial in rural network design. The underlying requirement is to ensure that voltage drops do not exceed specified levels.

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