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Research Article

Optimization of High Voltage Distribution System

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Abstract: This study presents a technique applied during the conversion of an existing Low Voltage Distribution System into a proposed High Voltage Distribution System in a radial distribution network. High Voltage Distribution System optimization is demonstrated using linear programming techniques in MATLAB optimization toolbox. An application has been developed to illustrate the methodology. The optimization technique estimates the optimal number of unit transformers in the proposed network which is equivalent to a bulk transformer in the existing network. Results showed that the optimization process produced nine 16 kVA and four 25 kVA unit transformers which is equivalent to a 315 kVA bulk transformer. This procedure is effective for converting the bulk transformer in the existing network into an equivalent population of unit transformers in the proposed network. To achieve the benefit of the conversion process, High Voltage Distribution System optimization has been recommended to minimize transformer no-load losses. As a result, the economy of distribution transformers is improved by savings in operational cost.

Keywords: HVDS, LVDS, optimization, radial distribution network, transformer no-load losses

INTRODUCTION

In a radial distribution network, two basic configurations can be deployed. The Low Voltage Distribution System (LVDS) or High Voltage Distribution System (HVDS). The Low Voltage (LV) network is characterized by a bulk transformer, which supplies multiple customers through 230/400V LV lines in most African countries including Ghana. This system is best suited for networks with concentrated loads and of high load densities. However, the primary distributors in the High Voltage (HV) network are the 11 kV lines. These lines terminate into short LV lines via smaller unit transformers to supply group of customers. The HV network is suitable for areas with scattered loads and low densities.

Network limitations such as future growth, voltage drop and thermal limitations on the LVDS may require voltage upgrade by migration to the HVDS (Ward, 2007). Moreover, the HV network is used for loss minimization, to replace the LV network, which is usually characterized by high technical losses (Amaresh *et al*., 2006). A major challenge in the HVDS scheme however, is the deployment of high numbers of transformers within the network. This is a high cost venture since transformers represent the largest capital investment in the distribution system and provide the best opportunity to reduce operational cost (Daut *et al*., 2006).

Transformers have fixed no-load and variable load losses. These losses are part of the functional parameters of the objective function for transformer design, which is known as the Total Owning Cost (TOC) (Hajipour *et al*., 2011). Hence, transformer loadings are necessary to meet required loads and load growth in a network with minimum losses. For these reasons, transformer selection takes energy losses into consideration. The no-load losses can be a major cost concern if the HV distribution network is overpopulated with unit transformers. This is because the aggregated sum of these losses increase the total cost of the system losses and hence the operational cost of the network. Therefore, migration to the HVDS scheme requires prudent allocation of loads to unit transformers.

Typically, in a rural HVDS scheme, a smaller unit transformer is allocated to a pump-set by load sanction apportioned to the consumer. This is the technique used by Agrawal and Patra (2011), to reduce technical losses in a rural LV network during conversion into HV network. Due to transformer increase, the sanctioned load rose from 210 kW in the LV network to 254 kW in the HV network. Thus, the absence of interest in load growth may simply result in over-investment.

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Load bifurcation and selection of small and appropriate size of transformers is similar to the load sanctioning. In this process loads are grouped and allocated to selected unit transformers in the proposed network (Gupta *et al*., 2012; Sarwar *et al*., 2012). The Electricity Company of Ghana (ECG) has implemented the HVDS project under Ghana Energy Development and Access Project (GEDAP). In this case unit transformers have been selected and distributed according to the order of existing load locations in the network. The limitation of these methods is that the transformer selection is based on the inspection of network load. The common objective however, remains avoiding over-populating or under-populating the network with unit transformers.

These techniques may result in the sub-optimal number of unit transformers in the HV network, from the standpoint of technical losses. In general, however, the techniques do not follow any well-defined optimization technique but they are rather based on simple logic that may easily be misleading. This study therefore, presents HVDS optimization technique, using linear programming approach with Matlab optimization toolbox. The methodology determines the optimal number of unit transformers in the HVDS. This will control the transformer no-load losses to improve the economy of distribution transformers in the network.

METHODS

The optimization process is informed by a decision rule which is a field representative network design consideration. In other words, this model draws its strength empirically from network design considerations which include:

- Average system loadings
- Transformer maximum no-load losses
- Rate of load growth and dispersion
- Transformer stockings ratio

According to Seifi and Sepasian (2011), the three steps needed to define the problem require the establishment of decision variables, constraints functions and the objective function.

Problem formulation: The mathematical model for the problem formulation is presented in the following discussions. The model contains an objective function that represents the total transformer capacity as a function of unit transformer size associated with the operation of the system. The objective function required to give the maximum kVA capacity of unit transformers is expressed as:

$$C_T = A * n_A + B * n_B \tag{1}$$

where,
C_T = Transformer total capacity (kVA)
A, B = Transformer sizes (kVA)
n_A = Number of A kVA Transformers
n_B = Number of B kVA Transformers

Constraints of the problem: In the optimization procedure certain constraints are imposed.The existing LV network and proposed HV network are placed on equitable grounds with respect to transformer no-load losses. In Inequality (2), the number of transformers in each network is multiplied by the associated no-load losses. The sum of the losses is therefore obtained as the total no-load losses, expressed as:

$$\underset{unit\ transformers}{sum\ of\ no\ load\ losses\ of} \le \underset{bulk\ transformer}{no\ load\ losses\ of}$$

$$NLL_A * n_A + NLL_B * n_B \le NLL \tag{2}$$

where,
NLL_A = No-load losses of transformer A
NLL_A = No-load losses of transformer B
NLL = No-load losses of bulk transformer

The next condition requires the average maximum loading in the existing network to be maintained for the proposed HV network. In Eq. (3), an inequality is developed to rationalize the number of unit transformers in the HV network. The left-hand side of Eq. (3) sums up the maximum loadings for each of the unit transformers. The transformers A and B can serve a maximum number of poles depending on the load demand per pole. Accordingly:

$$maximum\ system\ loadings\ in\ HVDS$$
$$\le maximum\ system\ loading\ in\ LVDS$$

$$D * p_A * n_A + D * p_B * n_B \le D * p_{LV} \tag{3}$$

where,
p_{LV} = Number of poles in LV network
p_A = Maximum number of poles assigned to transformer A
p_B = Maximum number of poles assigned to transformer B
D = Average demand per pole (kVA/pole)

In Eq. (3) is upgraded to In Eq. (4) by a load growth factor. This incremental factor technically increases the average maximum demand to accommodate more customers or service growth over a given period of time. It therefore follows that:

$$p_A * n_A + p_B * n_B \le p_{LV} * (1+r)^i \tag{4}$$

where,

Table 1: Design parameters for LV network

Parameter	Value
Maximum average system demand	216 kVA
Number of existing poles	36
Maximum average demand per pole	6 kVA
Bulk transformer capacity	315kVA
No-load losses of 315 kVA Bulk transformer	501 W

Table 2: Design parameters for optimized HV network

Parameter	Value
Maximum number of poles for 16 kVA	2
Maximum number of poles for 25 kVA	4
Maximum average demand per Pole	6 kVA
Unit transformers	16 kVA, 25 kVA
No-load losses of amorphous 16 kVA transformer	20 W
No-load losses of amorphous 25 kVA Transformer	28 W

Table 3: Effects of growth rate and transformer ratio

Parameter		Case I	Case II
Time period, i (years)		3	4
Network growth rate, r (%)		2	5
Growth factor $(1+r)^i$		1.061	1.215
Scale factor, N		1	3
Number of transformers	16 kVA	6	13
	25 kVA	6	4
Total transformer capacity (kVA)	246	308	
Maximum system loadings (kVA)	229	263	

Table 4: A summary of optimization results

N	No. of Transformers 16 kVA	25kVA	Total transformer capacity (kVA)	Maximum system loading (kVA)
2	9	4.5	244	216

i = number of years
r = Annual growth rate (%)

Equation (5) establishes the transformer mix in the network. The scale factor is chosen to reflect the load spread and the individual load sizes. For this model n_A is N times as many as n_B. Thus:

$$n_A = N * n_B \tag{5}$$

N = scale factor

Inequality (6) underscores the non-negativity of the number of transformers:

$$n_A, n_B \geq 0 \tag{6}$$

Problem modelling and solution: The general optimization problem is defined in Matlab by the statement expressed in (7):

$$\min_x f^T \text{such that} \begin{cases} Aineq.x \leq bineq \\ Aeq.x = beq \\ lb \leq x \leq ub. \end{cases} \tag{7}$$

where,
f = Linear objective function vector
Aineq = Matrix for linear inequality constraints
bineq = Vector for linear inequality constraints
Aeq = Matrix for linear equality constraints
beq = Vector for linear equality constraints
lb = Vector of lower bounds
ub = Vector of upper bounds

The solution algorithm is obtained by linear programming techniques in Matlab optimization toolbox. In this study a test application is used to explain the methodology.

Test application of the optimisation technique: The test application considered an existing LVDS network to be converted to HVDS. This was achieved by replacing the existing 315kVA bulk transformer in the LV network with16kVA and 25kVA unit transformers. The unit transformers were chosen based on network load assessment. Notably, the optimization process should be able to effectively harmonize with the network design conditions; that is, to determine the maximum number of unit transformersin the HV network. Hence, the problem in the expression (7) was modelled for maximization to enable the objective function to be maximized. Table 1 and 2 present the design parameters for the existing LVDS and proposed HVDS schemes.

We obtained the solution algorithm for Eq. (2) to Eq. (6) by linear programming. To test the robustness of the technique, growth factor and transformer ratio were varied to observe their effects on the number of transformers obtained (Table 3).

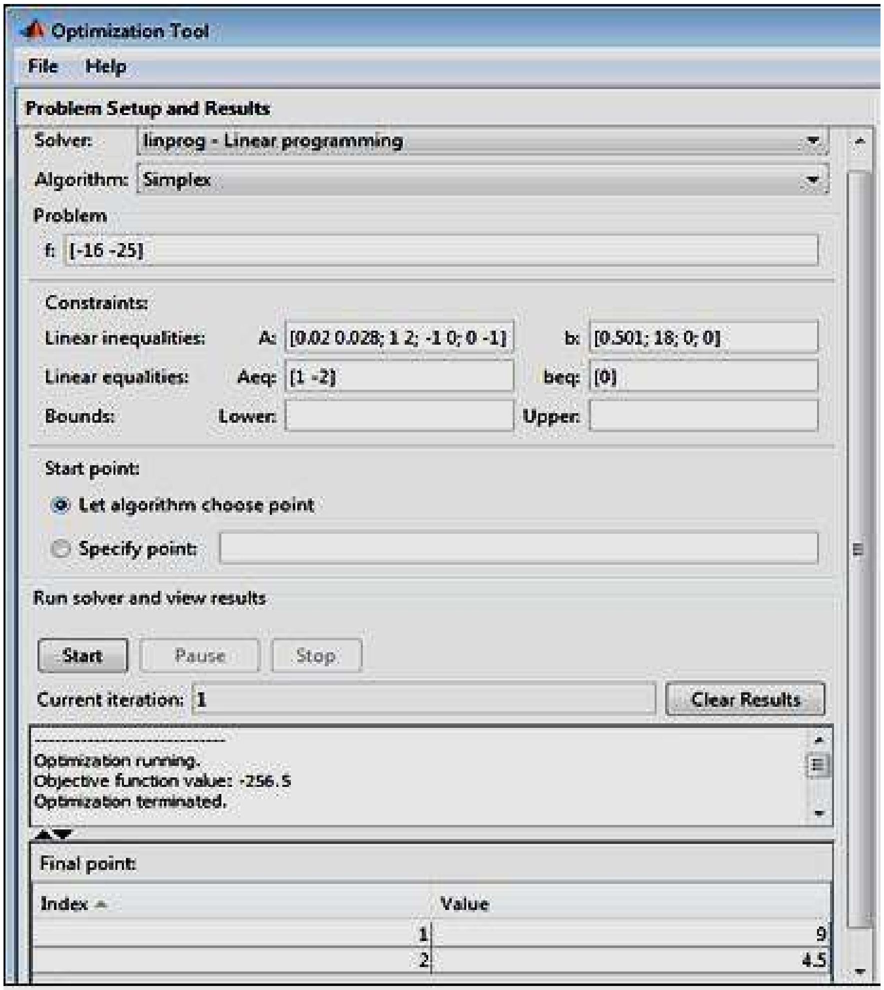

Fig. 1: Optimisation configuration and results with Matlab optimization toolbox

RESULTS AND DISCUSSION

The optimization configuration and result are presented in Fig. 1 as an output of the Matlab optimization toolbox.

Table 4 is a detailed summary of results for the proposed HV network.

In the transformer selection process, economic optimization is essential for to loss minimization. The optimization process presented in this study describesa method for selecting the optimal number and sizes of unit transformers, based on loss minimization. This resulted in four and a half 16 kVA unit transformers. The network designer could make a choice of four transformers for the following practical reasons; the need to avoid transformer increase in other to reduce no-load losses. The marginal lost capacity is insignificant compared to the reserved capacity of the network. Reserved capacity is inherent in the network because transformers usually, are not fully loaded (Gupta *et al*., 2012). From analytical considerations, the growth factor can be used to increase the number of transformers when deemed necessary. In addition, the choice of five transformers would have defeated the condition embodied in Eq. (4).

From Table 4, it is observed that in the base case the optimisation technique resulted in a maximum number of transformers with a total capacity of 224 kVA. This means that for a base case loading of 216 kVA, a large reserve capacity increases the no-load losses and hence the operational cost. Whenever necessary, the needed reserve capacity could be catered for by growth factor modification. The summary results obtained for changes in growth factor and transformer ratio are presented in Table 3.

The growth factor offers flexibility to increase or reduce the number of unit transformers in relation to variations in the network maximum average system loadings. The growth factor is able to cater for basic growth, for an increase in customer load requirement over a period. Additional service growth, as a result of new customer connections is also accommodated. This is evident in Table 3, where an increase in growth factor for 4 years at 5% growth resulted in an average maximum loading at 263 kVA. Correspondingly, an estimated number of unit transformers were predicted at four and thirteen 25 kVA and 16 kVA respectively. Technically, transformers can be gradually retrofitted as load grows over the years without compromising with on no-load losses. This technique therefore, predicts transformer numbers based on network growth rate and load sizes.

An advantage of this technique is the regulation of the no-load losses. Based on the foregoing discussions, the authors realize that optimization is significant in order to reap the full benefits of the HVDS scheme. It should be noted that this technique is not meant to completely determine exact transformer numbers, but serves as a guide leading to such a determination in practice. In addition, the model assumes the same pole positions in both networks. This is not necessarily the case in practice. The technique is limited to HV distribution network as a product of migration from an existing LV distribution network.

CONCLUSION

A linear optimization technique for the selection of unit transformers in the HVDS has been presented. There is limited literature that deals with the selection of the number and sizes of unit transformers in the HVDS scheme. This study therefore provides a basis for determining the optimal number and sizes of unit transformers for HVDS schemes. The process results in the control of transformer no-load losses and the reduction of operational costs in distribution systems. The optimization process can be extended to more than three transformer sizes within a network.

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