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Determination of Optimum Number of Unit Transformers for High Voltage Distribution System

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***Abstract*— This paper presents a technique applied during the conversion of an existing Low Voltage Distribution System (LVDS) into High Voltage Distribution System (HVDS) in radial networks. HVDS optimization is demonstrated using linear programming techniques in MATLAB optimization tool box. A test application results explain the methodology. The optimization technique proposed estimates the optimal number of unit transformers in the HVDS. This procedure is effective for converting the bulk transformer in the LVDS into an equivalent population of unit transformers in the HVDS. The benefit of the conversion technique is the minimization of transformer no-load losses. As a result, the economy of distribution transformers is improved by savings in operational cost.**

***Keywords*— HVDS; LVDS; optimization; optimal number; transformer no-load losses**

I. INTRODUCTION

LVDS and HVDS are two basic configurations of the electrical power distribution system. The LVDS is characterized by a high capacity transformer at a load centre, which supplies multiple customers through long low voltage (LV) lines such as 0.415kV. In the HVDS, high voltage (HV) lines such as 11kV are the primary distributors. In this case smaller unit transformers terminate at the HV lines to supply fewer customers via short LV lines. Network limitations such as future growth, voltage drop and thermal limitations on the LVDS may require voltage upgrade by migration to the HVDS [1]. The HVDS scheme will improve voltage profile and minimize technical losses, especially in rural networks with high loss long LV lines occasioned by dispersed loads [2]. A major challenge in the HVDS scheme however, is the high cost of transformers; since it represents the largest capital investment in the distribution system, and provides the best opportunity to reduce operational cost [3]. As a result, transformer loadings are required to meet load expectations in a network with minimum losses. To load a transformer in a most economical way therefore, means minimizing the sum of no-load and load losses. The no-load losses in particular present themselves as soon as the transformer is energized. Since distribution transformers are run throughout the year, it is advantageous for utilities to reduce these iron losses [4]. 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 increases the total cost of system losses, and hence the operational cost of the network. Therefore, migration to the HVDS scheme requires prudent allocation of loads to populated smaller unit transformers. The common objective however, remains the need to avoid over-populating or under-populating the network with unit transformers. For instance, in a rural HVDS scheme for agricultural consumers a smaller unit transformer is allocated to a pump-set by load sanction apportioned to the consumer. Several case studies have provided support for sanction loading [5-6]. Also in [7], loads have been sanctioned in an attempt to reduce technical losses and cater for load growth in a rural network. The resulting increase in the no-load losses is attributed to additional transformers. On the other hand, the technique of load bifurcation has been applied to transformer allocation according to load sizes [8]. In practice, these loads are grouped and allocated to transformers by inspection. A similar field practice involves loading each unit transformer to a fixed percentage in proportion to its size and load proximity. This is the procedure adopted by the Electricity Company of Ghana (ECG) for HVDS projects. From the standpoint of transformer no-losses these techniques could result in a sub-optimal manner of populating the HVDS network with unit transformers; they do not follow any well-defined scientific principle. The main contribution of this paper therefore, is to present HVDS optimization technique using linear programming approaches with Matlab optimization toolbox. The methodology determines the optimal number of unit transformers to improve the economy of distribution transformers.

II. TEST APPLICATION

A test application considers a model of an existing LVDS network with parameters as shown in Table 1. In the conversion process our primary concern is the transformer population. Thus, the LVDS network is converted to HVDS using 16kVA and 25kVA three-phase amorphous transformers to replace the existing 315kVA three-phase bulk transformer. In this case, the transformer sizes are chosen to reflect the load sizes within the network. The existing transformer was loaded by 68.5%. Table 2 presents the design parameters for the HVDS scheme. In both tables, the kVA values presented are rated from the manufactures data provide by ECG.

TABLE I. DESIGN PARAMETERS FOR LVDS

Parameter	Value
Maximum average System Demand (kVA)	216
Number of Existing Poles	36
Maximum Average Demand /Pole (kVA)	6
Bulk Transformer Capacity (kVA)	315
No-load Loss of 315 kVA Bulk Transformer (kW)	0.501

TABLE II. DESIGN PARAMETERS FOR HVDS

Parameter	Value
Maximum Number of Poles for 16 kVA	4
Maximum Number of Poles for 25 kVA	2
Maximum Average Demand /Pole (kVA)	6
Unit Transformers (kVA)	16, 25
No-load Loss of Amorphous 16 kVA Transformer (kW)	0.020
No-load Loss of Amorphous 25 kVA Transformer (kW)	0.028

III. OPTIMIZATION TECHNIQUE

An engineering design decision problem is a problem of taking a decision with multiple criteria [9]. Such a decision is aimed at increasing performance, and invariably minimizes cost in this case. Hence, this technique is informed by a decision rule which is an empirical field network design considerations characterized by;

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

The steps required to define the optimization problem are established [10];

A. Problem Formulation

Decision variables

n_{16} = number of 16 kVA Transformers
n_{25} = number of 25 kVA Transformers

Constraints of problem

Inequality (1) limits transformer iron losses due to overpopulated unit transformers, hence,

Sum of no-load losses of smaller unit transformers ≤ no load loss of bulk transformer

$$0.020*n_{16} + 0.028*n_{25} \leq 0.501 \qquad (1)$$

The average maximum loading of 216 kVA was transferred from the existing network to the HVDS. The 16kVA and 25kVA transformers could go up to two poles and four poles for a 6 kVA maximum demand per pole in that order. This resulted in a total load of 12kVA and 24kVA for each transformer respectively. However, a load growth incremental factor increased the average maximum demand to accommodate service growth over a given period of time. Thus, (2) satisfies the loading conditions for the converted network.

Maximum system loadings in HVDS ≤ Maximum system loadings in LVDS

$$12*n_{16} + 24*n_{25} \leq 216*(1+r)^{i} \qquad (2)$$

where,

i = number of accumulated years and

r = growth rate (%)

Equation (3) and (4) are listed as the transformer mix and non-negativity constraints respectively.

$$n_{16} = N*n_{25} \qquad (3)$$

$$n_{16}, n_{25} \geq 0 \qquad (4)$$

where, N = transformer ratio

Objective function

The objective function is to be maximized, so f in (7) is negated. The function which is required to give the maximum capacity of the unit transformers is:

$$f = 16*n_{16} + 25*n_{25} \qquad (5)$$

where, f is the total transformer capacity in kVA.

B. Problem Modeling

The general optimization problem is defined in [11] by the statement expressed in (6)

$$\min_{x} f^{T} \text{such that} \begin{cases} Aineq.x \leq bineq \\ Aeq.x = beq \\ lb \leq x \leq ub. \end{cases} \qquad (6)$$

The solution algorithm was obtained for (2) to (4) by linear programming [11]. To test the robustness of the technique, growth factor and transformer ratio were varied to observe their effects on the number of transformers obtained.

IV. RESULTS AND DISCUSSIONS

The optimization results were obtained from the matlab optimization tool box. They are presented in the following cases.

A. Base Scenario

A base year summary of results is presented in Table 3 for the optimal number and total capacity of transformers obtained.

TABLE III. A SUMMARY OF RESULTS ON OPTIMIZATION

N	No. of Transformers		Total Transformer Capacity (kVA)	Maximum System Loading (kVA)
	16 kVA	25kVA		
2	9	4.5	244	216

In populating a network with unit transformers no-load losses should be reduced by avoiding transformer increases. These losses play an important part in loss minimisation techniques. But the HVDS concept in itself is a loss minimization technique [12]. Therefore, it is important to be cautious with transformer numbers in order to control the no-load in the HVDS scheme. From Table 3, the optimization process generated an estimate of nine 16 kVA and four 25 kVA unit transformers in the base year at an average maximum system loading of 216 kVA. The resulting total transformer capacity of 224kVA is able to tolerate suppress demand due to its reserved capacity; after all the loads may never reach their coincidence at the same time. In addition, a HV network exhibits low loss capabilities and hence holds reserve capacity as a complement.

B. *Significance of Growth Factor*

The summary results obtained for changes in growth factor and transformer ratio are also presented in Table IV.

TABLE IV. EFFECTS OF GROWTH RATE AND TRANSFORMER RATIO

Parameter		Case I	Case II
i (years)		3	4
r (%)		2	5
Growth Factor $(1+r)^i$		1.061	1.215
N		1	3
Number of Transformer	16 kVA	6	13
	25 kVA	6	4
Total Transformer Capacity (kVA)		246	308
Maximum System Loadings (kVA)		229	263

On the other hand, the growth factor offers flexibility to increase or reduce the number of unit transformers by variations in the network maximum average system loadings. It is able to cater for basic growth, for an increase in customer load requirement over time. Additional service growth as a result of new customer connections is also accommodated. This is evident in Table 4 where an increase in load growth factor for 4years at 5% growth estimates the average maximum loadings at 263 kVA. Correspondingly, an estimated number of the additional unit transformers are predicted. This allows for gradual injection of transformers as load grows over the years without compromise on needless no-load losses. This technique therefore, predicts transformer numbers based on network growth rate and load sizes, which determine the nature of transformer mix. An advantage of this technique is the regulation of the no-load losses. Based on the foregoing discussions, optimisation is significant in order to realise 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.

V. CONCLUSION

i. This study presented optimization technique as a basis for determining optimal number of unit transformers for HVDS projects.
ii. The technique is proposed for distribution network designers and planners in the control of transformer No-load losses to reduce operational cost.
iii. The process would reduce computational complexities with transformers and loads in large HVDS networks employing optimization techniques
iv. To further this work, the objective function could be chosen as a cost function with economic constraints.
v. For future studies, the optimisation process can be extended to more than two transformer sizes.

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