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Evaluation of Higher Distribution and/or Utilization Voltages

Final Report

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Prepared for:

U.S. Department of Energy

Assistant Secretary for Resource Applications

Office of Electric Energy Systems

Under Contract No. AC01 78 ET 20505

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Evaluation of Higher Distribution and/or Utilization Voltages

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Prepared by:

Dr. George A. Hazelrigg Jr.

Econ, Inc.

Princeton, New Jersey 08540

AC01 78ET 20505

Prepared for:

U.S. Department of Energy

Assistant Secretary for Resource Applications

Office of Electric Energy Systems

Washington D.C. 20461

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NOTE TO READER

This report is a summary of work completed under Contract No. ET-78-C-01-2866 for the U. S. Department of Energy, Office of Electric Energy Systems. The detailed investigations are documented in five interim reports which are described in Appendix A to this report and are available upon request from

Philip N. Overholt
U. S. Department of Energy
Office of Electric Energy Systems
Mail Station 3344
12th and Pennsylvania Avenue, N.W.
Washington, DC 20461
(202) 633-8483

ABSTRACT

An electric energy distribution/utilization system cost analysis model is presented for exploring cost tradeoffs (capital investment, operation and maintenance and cost of losses) and optimizing system configuration. The model focuses on the treatment of residential and light commercial service areas with time-varying load characteristics, including customer load profile changes, per customer load growth and service area population growth. Applications of the model are discussed. These include providing insight on: the selection of primary and secondary voltages; conductor sizing; distribution transformer sizing, change out policies and copper-to-core-loss ratio; and limits on allowable voltage variation at the service entrance. Examples are provided to illustrate model capabilities.

NOTE OF TRANSMITTAL

This report is submitted in fulfillment of the requirements of Department of Energy Contract No. ET-78-C-01-2866. It comprises a summary of detailed investigations which are fully documented in five interim reports:

1. First Interim Report, "Literature Search and Problem Definition," December 31, 1978.
2. Second Interim Report, "Identification of Components and Parameters for Cost and Energy Efficiency Analysis," March 30, 1979.
3. Third Interim Report, "Analysis of Individual Component Cost and/or Energy Efficiencies," October 26, 1979.
4. Fourth Interim Report, "Assessment of Optimum Distribution Configuration," August 29, 1980.
5. Fifth Interim Report, "Assess Constraints to Higher Voltage Implementation," September 5, 1980.

Appendix A describes these reports in more detail

The ECON study manager for this effort has been Dr. George A. Hazelrigg, Jr. In addition, the following members of the ECON staff have contributed to this effort: Ms. Carol Prevost, Messers. Fred H. Clyne, David Reid, David Lawson and Joel S. Greenberg. Electric motor models were developed by Professor Joseph Winston of the New Jersey Institute of Technology.

The Philadelphia Electric Company participated as a subcontractor in this study. Dr. R. Barnett Adler has been the PECO study manager. Key study members at PECO were Messers. William G. Kirn and Stephen T. Matraszek. A considerable contribution to this study was also made by the Electrical Engineering Division of PECO. Individuals from this division participating in the study included Messrs. John F. Gillespie, George T. Brecht, Barry N. Hornberger, Walter S. Lacey and Thomas J. Tucker. Also acting as consultants to PECO on this study were Professor Lawrence Eisenberg of the University of Pennsylvania and Professor Ronald G. Wasley of Drexel University.

This study benefited greatly from the technical guidance of Messers. Philip Overholt and Kenneth W. Klein of the U.S. Department of Energy.

G. A. Hazelrigg, Jr.
Director, Systems Engineering

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INTRODUCTION

Recent real increases in the cost of electric energy generation, combined with the expectation that this is a continuing trend, provide an economic incentive to search for opportunities to improve the efficiency of the electric distribution system and end-use devices. This incentive is evidenced in the recent literature through an increasing emphasis on energy losses [1, 2], particularly discussions on the selection of conductor sizes [3], transformer rating [4-8], load management [9] and voltage regulation [10, 11].

Optimization of electric distribution system design has been a topic of concern for several decades. During the late 1950s and early 1960s, a number of papers, authored by equipment suppliers, appeared addressing system economics, planning and design, e.g., [12-16]. Through the 1960s, many utilities implemented system changes to effect various potential economies. These efforts resulted in a second round of papers, emanating from utilities, lauding the effectiveness of these actions, e.g., [17, 18].

Since these earlier efforts, three changes have taken place to warrant reconsideration of the problem: fuel shortages and rising prices have placed an increasing emphasis on conservation through efficient system design; distribution and utilization system component technologies have advanced providing a broader range of choice; and computational capabilities have advanced enabling more detailed treatment of complex problems. These changes form the basis of the present effort.

The optimal design of an electric distribution system involves tradeoffs in the selection of the individual components (conductors, transformers, etc.) and their arrangement to meet energy demand while satisfying reliability, voltage regulation and other constraints. Tradeoffs must be made in consideration of capital investment costs, operation and maintenance (O&M) costs, and energy loss costs (including both energy cost and system capacity cost), over a planning period (e.g., 30 years). In addition, tradeoffs must account for customer costs, including losses in the utilization system and end-use devices. Total costs also depend on the cost of energy, load density, load profile, load growth, and so on, year by year over the planning period, and on the manner by which the circuit service area develops over time.

This report presents a computer model for simulating the sequence of capital investments in a distribution system as the system develops to provide a safe, reliable and quality electric energy supply to a growing (or declining) residential load. The model also evaluates energy losses and their cost and system O&M costs, year by year, over the planning period. It includes a customer submodel which provides costs and losses of the residential customer's system and appliances. The principal features of the model include the capability to simulate aerial or underground construction (or a mixture of the two); the consideration of primary distribution voltages of 13 kV to 69 kV and secondary/utilization voltages ranging from 120V to 960V (single- or three-phase); the capability of considering degree of "homogeneity" of the area's residential development; the capability to treat year-by-year changes in rate of residential development, changes in load characteristics, and changes in cost of energy, over the study period; and the option to run in either an analysis or system optimization mode.

The emphasis of this summary report is on a description of the model. This includes a review of the procedure used in developing the model and a discussion of the factors and constraints incorporated in it. The analysis and optimization modes of the model operation are also discussed and examples of the use of the model are provided. Examples include analysis of the choice of primary and secondary voltages and conductor sizes, and the impact of the cost of energy losses.

The study upon which this report is based also includes a net energy analysis methodology. This methodology enables a net energy comparison of alternative system configurations.

DESIGN-POINT STUDIES

A set of design-point studies provides the foundation for the distribution/utilization system cost analysis model. Each of these studies is a detailed investigation of a component (or component ensemble) or a system of components at a specific "design point." For a component, the design points sample the range of voltage and/or current ratings that might be required in the model. Calculated are component cost, a characterization of losses and requirements for safe, reliable performance. For a system, the design points include a sampling of customer peak demands and lot sizes, and a sampling of primary and secondary distribution voltages. Calculated are the nature and number of each component

required to perform the system function in a feasible manner and the total cost of the system.

The design-point studies provide a systematic means of accessing relevant knowledge and experience on components and systems to be modeled.

Distribution Components

The distribution component design-point studies establish cost and energy loss data for all the components used in the distribution substation, primary and secondary circuits. Primary voltages selected as design points include 13, 34 and 69 kV. Secondary voltages included 120/240V, 240/480V and 480/960V, single-phase, and 208Y120V, three-phase. Current ratings sample the range likely to be encountered in the use of the distribution model.

In many cases, components are grouped into ensembles which are commonly found in the distribution system. These include the aerial support structure, and assemblies which include a cutout and surge arrester such as the terminal pole and the distribution transformer.

Utility experience provided the basis for specifying costs and loss characteristics for components rated at 13 and 34 kV. Estimates for currently unavailable distribution-class components rated at 69 kV were made using engineering judgment following consultation with equipment manufacturers. Such components included load-break elbows and distribution-class surge arrestors.

Regression curves were fit to cost and loss data for each component to model these quantities as functions of component voltage and other relevant specifications. For instance, the capital and O&M costs for distribution transformers are expressed as functions of primary and secondary voltages and number of phases and rating. Similar functions are derived for transformer resistive and fixed core losses. All costs are given in 1979 dollars. All component costs, energy loss functions and supporting data are given in [19].

Also, as part of the component studies, information was assembled to support the calculation of a capital carrying charge rate to convert capital cost into a levelized annual revenue requirement. Components vary in tax and book life and in mortality dispersion.

Distribution Substation

A standard substation design is adopted for the model. Standardization provides advantages such as better estimates of construction costs, lower equipment costs through the purchase of large-lot quantities, fewer spare components to cover equipment failures, lower O&M costs through standardization of work procedures and use of specialized test equipment. Finally, a standard design may provide capital savings by coordinating the choice of substation components in satisfaction of performance requirements.

The substation is designed according to the unit concept. In this design, Fig. 1, the reactance of the power transformer is chosen so that the maximum available fault current is limited to about 15 kA (well within the interrupting capacity of the standard 1200 A low-side circuit breaker). Furthermore, the capacity of the transformer is chosen so that full-load, low-side current is 1200 A (matching the nominal rating of the circuit breaker). This capacity is divided into three 400 A circuit feeders. Each feeder is switched by a motor-operated disconnecting switch. When a fault occurs on any one of the three circuits, the circuit breaker opens momentarily, and recloses after the switch for the faulted circuit has opened. This switching sequence is completed in less than one second.

Design-point studies examined substations supplied by 230 kV transmission and serving primary distribution circuits at 13, 34 and 69 kV. The results of these studies are found in [19].

Distribution Circuit

Circuit design-point studies were performed to establish the configuration, constraints and interrelationships governing the design and development of a distribution circuit. They also identified any special problems that might be encountered as primary and secondary voltages increase above 34 kV and 120/240V respectively.

Fig. 1. Substation configuration (unit concept).

A circuit design point consists of the specification of the circuit configuration, construction type (aerial/underground), nominal current rating, and primary and secondary voltages. In addition to these specifications, area load data are given, including the average peak demand of an individual residence, the peak diversity function and the average residential lot size. The circuit design-point studies provide information on model design and validity including circuit configuration, circuit design procedure, circuit design constraints, appropriate assumptions for simplifying the model and considerations with higher primary and secondary voltages.

One purpose of the circuit design-point studies was to provide a basis for selecting an appropriate circuit configuration. The configuration selected is illustrated in Fig. 2. It is characterized by an odd number of primary lateral pairs whose spacing is dictated by the length of the secondary circuit. The secondary circuits extend an equal distance out from the distribution transformer to serve the area between the lateral pairs. A distribution transformer is located at each cross street. The secondary circuit runs along the cross street and serves residential lots on each side.

This configuration allows a tradeoff between area coverage of primary and secondary circuits. With long secondaries, fewer or shorter primary laterals are required to supply a given area.

Fig. 2. Circuit configuration selected for the model.

The underground feeder connecting the substation and primary main is assumed to be of length proportional to the square root of the area covered by the circuit.

End-User System

A number of potential end-user systems (customer's meter, breakers, circuits, switches and outlets) were studied and modeled. These included single- and three-phase,

and single and dual voltage systems. Convenience outlet voltages up to 250V were considered, with the lower voltages being obtained from an autotransformer in the case of higher single voltage secondary systems. Safety dictated the use of ground fault circuit interrupters for all secondary voltages above 120V.

In all cases, end-user capital costs were modeled as a function of system voltages and configuration. O&M costs were assumed to be independent of voltage and configuration and losses in the end-user circuits were found to be negligible with the exception of the autotransformer (when included in the system).

End-Use Devices

End-use devices were classified as resistive loads and motor loads. Motor design-point studies were performed on universal, shaded-pole, split-phase, capacitor and three-phase motors for fractional horsepower and up to 5 hp. Motor efficiency and power factor were modeled as a function of voltage, horsepower rating and motor type. These studies noted potential problems with smaller motors, especially universal motors, designed to operate at higher voltages.

Resistive end-use devices were assumed to be essentially unaffected by voltage (other than current rating).

MODEL OVERVIEW

The distribution/utilization system cost analysis model evaluates the present worth of all distribution and end-user system costs that are affected by choice of primary and secondary voltages and by the distribution system design, in order to facilitate cost comparison of system alternatives. The model simultaneously assures that a variety of system constraints are satisfied. It includes an optimization capability that enables cost minimization with respect to a set of "control" variables such as conductor sizes, primary voltage and secondary voltage. Other variables, such as customers per secondary circuit and number of laterals per circuit, can be optimized by enumeration.

Details of the model are provided below.

Substation and Circuit Configuration

The substation configuration chosen for this model is based on the unit concept discussed in the previous section and shown in Fig. 1. This substation

supplies three circuits, each rated at 400 A. Accordingly, the circuit capacity and, hence, also circuit area, are proportional to the primary voltage.

The circuit configuration modeled is shown in Fig. 2. The circuit area is rectangular with its length determined by the length of the secondary circuit and the number of lateral pairs. The circuit width is then chosen to provide a circuit area of size commensurate with the circuit capacity (MVA) and the maximum load density during the planning period.

The circuit is supplied by an underground feeder and can be switched into adjacent circuit areas to enhance reliability.

Customer Load Characterization

The residential customer's load is characterized by an annual peak demand, and diversity and loss factors as a function of the number of customers comprising the load and the secondary voltage. These are sufficient to reflect changes in the nature of the customer's load as may result from load management strategies as well as use of dispersed generation and storage.

Customer loads, shown in Fig. 3, can be classified as resistive loads and motor loads. In this model it is assumed that the efficiency of the resistive loads is independent of secondary or utilization voltage. Thus the energy demand of the resistive loads is voltage invariant. Motor efficiency, on the other hand, does vary slightly with voltage. That fraction of the customer load which is motor load is

adjusted to account for differences in motor efficiency as a function of voltage. The adjusted total load is used to scale the customer peak load.

An average value is used to represent peak demand for each of the residences in a circuit's service area. The average value is specified for each year of the study period and, as shown in Fig. 4, need not be monotonically increasing.

Fig. 3. Electricity use in the residential sector, 1975.

Fig. 4. Average annual residential customer peak demand.

The customer's load profile is accounted for by specifying an annual peak diversity factor, $DIVFAC(n)$, as a function of the number of residences, n , in the load sample. The peak diversity factor is calculated from hourly residential load samples as

$$DIVFAC(n) = \frac{\max_{j=1,8760} \left\{ \sum_{i \in A_n} S_{ij} \right\}}{\sum_{i \in A_n} \max_{j=1,8760} \left\{ S_{ij} \right\}}$$

where S_{ij} is the i^{th} customer's demand in the j^{th} hour of the year and A_n is one sample of n customers out of many considered. Representative functions for diversity factor are found in [20, 21]. Alternate means of estimating $DIVFAC(n)$ are discussed in [4].

The remaining parameter characterizing the customer's load profile is the loss factor associated with a sample of n customers. The loss factor is the ratio of the average hourly loss to the peak hourly loss. It is given by

$$LOSFAC(n) = \frac{1}{8760} \frac{\sum_{i \in A_n} \sum_{j=1}^{8760} S_{ij}^2}{\max_{j=1,8760} \left\{ \sum_{i \in A_n} S_{ij}^2 \right\}}$$

Approximate expressions for $LOSFAC$ in terms of load factor are given in [7, 21]. Functions collected by a survey of utilities are given in [21].

Area Load Modeling

In order to account for the dynamic characteristics of a circuit service area (i.e., growth), two new system parameters are defined. The first, shown in Fig. 5, is referred to as the Fullness Factor. The Fullness Factor is the fraction of lots in

Fig. 5. Fullness factor and component count.

the service area which have load. Typically, the Fullness Factor will increase over time. The Fullness Factor relates to the number of components of the i th type, N_i , through the second parameter which is referred to as the Homogeneity Factor, H , shown in Fig. 6. The Homogeneity Factor describes the extent to which the occupied areas of the service area are uniformly distributed throughout the service area as opposed to being confined to compact locations within the service area. In so doing, the Homogeneity Factor provides a relationship between the Fullness Factor and the number of each type of component required to serve the load. The number of the i th type of component, N_i , is given in terms of the maximum number of components, $N_{\max i}$, that would be required if the service area were fully developed, the Fullness Factor and the Homogeneity Factor for that particular component. Typical Homogeneity Factors are as follows: for the main, $H=1$ since the total main is required regardless of how the initial load is distributed; for the service connections, $H=0$ since no capacity is in excess of need; and for secondaries and laterals, H is between 0 and 1. Homogeneity Factors may be determined by the relationship

$$H_i = \frac{\left(\begin{array}{c} \text{No. of} \\ \text{Components} \end{array} \right)_i - \left(\begin{array}{c} \text{Min. Possible No.} \\ \text{of Components to} \\ \text{Serve Load} \end{array} \right)_i}{\left(\begin{array}{c} \text{Max. No. of} \\ \text{Components} \end{array} \right)_i - \left(\begin{array}{c} \text{Min. Possible No.} \\ \text{of Components to} \\ \text{Serve Load} \end{array} \right)_i}$$

Fig. 6. Homogeneity factors.

the service area which have load. Typically, the Fullness Factor will increase over time. The Fullness Factor relates to the number of components of the i th type, N_i , through the second parameter which is referred to as the Homogeneity Factor, H , shown in Fig. 6. The Homogeneity Factor describes

The advantages of the Fullness and Homogeneity Factors are that they provide a means for analyzing the effects of load growth over time within a circuit service area without being specific as to the location of specific elements of load.

Using these factors, one determines, year by year over a study period, the number of components of each type necessary to serve the load. It is then possible to account for their capital and O&M costs during the period of time which each is required.

It is assumed that equipment is not removed after its installation. Equipment which is installed is sized at installation to handle at least the maximum load and it is, in general, not changed out as load increases. There is one exception, that is the distribution transformer. There is provision in the model to allow for changeout of the distribution transformer as load increases.

Circuit Design Procedure

The approach to specifying circuit components begins with the establishment of a feasible secondary circuit design. Secondary length and conductor size and customer service connection are chosen to avoid excessive voltage drop, intolerable voltage fluctuation and currents greater than conductor thermal ratings.

The peak demand of the secondary circuit establishes the nameplate rating of the distribution transformer. Typically, the initial loading on a transformer will be 90 to 100 percent of its nameplate rating. The transformer will be replaced by one of greater capacity when its load reaches somewhere between 140 and 180 percent of nameplate rating. Transformer rating and changeout policies are possible areas for optimization.

The length of the secondary circuit establishes the distance between adjacent primary laterals; the length of these laterals is arbitrary. The circuit area is chosen to load the circuit ultimately to its nominal rating (400A). Therefore, for a given circuit area length, the number of laterals may be calculated since their spacing is known or, if the number of laterals is specified, their length may be calculated. The circuit area length is the length of the primary main. The length of the lateral may be constrained by reliability considerations as are the number and types of sectionalizing switches that are needed.

The lateral conductor size is checked for adequate thermal rating as are the conductors used in the primary main and the circuit feeder. As it is assumed that the voltage at the circuit end of the feeder is maintained at the high end of the range of allowable voltage variation by the substation LTC transformer, the voltage drop from this point to the most remote distribution transformer is

calculated. In a feasible design, this voltage drop may not exceed a maximum value allotted to the primary circuit. Similarly the voltage drops under peak loading may not exceed the specified maximum allotments for the distribution transformer, secondary circuit and service connection respectively.

Once the secondary length, the number and length of laterals and conductor sizes have been specified, a complete bill of materials for the circuit may be written. From this and the data developed in the component design-point studies, the total capital cost of the circuit may be calculated.

Circuit Design Constraints

There are four constraints that a feasible circuit design must satisfy under normal conditions:

Thermal rating of conductors: the model checks peak power flows on cables to assure that load does not exceed thermal rating.

Voltage regulation: voltage variation at the customer's meter is held within a specified tolerance.

Voltage fluctuation: transient voltage fluctuations due to local motor starts are maintained at a tolerable level.

Reliability: reliability standards are met by means of manual and supervisory controlled sectionalization to maintain consistent average annual availability of service in accordance with current utility practice [22].

MODEL LOGIC

The model main routine logic is presented in Fig. 7. First, the input routine is called to read all input variables. Next, the control variables (those which can be optimized) are initialized to the values read in by the input routine. Then the names of any variables which are to be optimized are read. Lower and upper bounds on each variable are read along with the maximum error permitted between the calculated optimum and the true optimum.

After the optimization variables have been read, selected input data are stored in auxiliary arrays. These data are needed at the beginning of each optimization iteration.

The program then checks to see if any variables are to be optimized. If there are no optimization variables, the system development and cost evaluation routine,

Fig. 7. Main routine logic.

FOFX, is called and the annual system development and costs are calculated along with a total present worth cost per square mile for the distribution circuit capital and losses as well as the customer system capital and loss costs for each of the years of the specified study period.

If there are variables to be optimized, a do-loop is entered which calls FBSRCH for each of these variables in turn. The FBSRCH routine performs a Fibonacci search of the span defined by the variable upper and lower bounds specified in

the input data. The search is designed such that the optimal value of each variable is guaranteed to differ from the true optimum by no more than the maximum error specified in the input data. For each iteration in the search, the FOFX routine is called to evaluate system cost.

At the end of each Fibonacci search, the value of the optimized variable replaces the value of that variable in the base data. Control is then returned to the main routine after which simulation is performed once more with all control variables set to their optimum values.

The FOFX routine logic is shown in Fig. 8. FOFX simulates the development and operation of a distribution circuit and associated substation capacity over a specified study period, for a given set of base data. The routine calculates the number of components required for a circuit area for each year of the study period. The losses on the circuit are also calculated for each year and the present worth of the component capital, O&M and loss costs is summed over the study period and divided by the number of square miles in the circuit area to calculate the objective function, the total cost per square mile of load served.

If no overload is encountered, a secondary load flow model is developed. This model is used to check the voltage drop on the secondary for the secondary peak year and to compare the peak secondary load with the rating of the secondary cable for underground cases. If an overload exists an error message is printed.

If no overload is encountered, the frequency with which each possible magnitude of transient voltage fluctuation is experienced by a secondary customer is calculated. The frequency associated with each magnitude of voltage fluctuation is then checked against an irritability curve to determine if the secondary circuit is feasible as designed. If the voltage fluctuation is tolerable, the dimensions of the circuit needed for the peak year and the maximum number of each type of component required for a fully developed circuit are calculated.

Next, the sectionalizing requirements to limit annual average unavailability to below a specified maximum are determined. This may involve the installation of manual and supervisory controlled switches to limit the amount of load dropped for any extended period of time to a specified value.

At this point, an ac load flow model for the secondary, lateral, main/feeder and the total circuit is set up. A voltage profile for the primary and secondary circuits is calculated as a check for low voltage points. Capacitors are added to specified points along the laterals in increments until the low voltage problems are overcome. In an underground case, the ratings on the lateral and main cables are checked for overloads. The feeder cable rating is also checked for an overload. If any cable is overloaded, a message is printed and the program returns.

If no overloads are encountered, a loop is entered and executed once for each study year. Three computations comprise this loop. First, the number of components required for the current year to supply the circuit load is calculated. This is used to calculate the annual capital cost. Next, the annual I^2R loss, transformer core loss and peak demand losses are calculated, either with the loadflow models or algebraically. The appropriate coincidence and loss factors (which depend on number of customers served) are considered for each subsystem (e.g., secondary, lateral, etc.) in calculating the total system loss. The current-year circuit load and system development are also considered.

Last, the per-unit cost of each type of component is calculated and combined with the number of units to determine the current year's levelized capital cost in present worth terms. Distribution transformer changeout costs are accounted for

when they occur as well as the increased costs of the transformers. The current year's present worth of loss cost is then added to the capital cost. Finally, the number of customer components and their cost in present worth terms is calculated and added to the accumulated discounted system cost, along with the capital and loss costs.

For each year, a summary of the numbers of components, losses and associated present worth levelized costs accumulated by the present year is printed. In the last year, the accumulated cost during the circuit life is normalized by dividing it by the number of square miles per circuit. This value is then used for the objective function which is returned either to FBSRCH or the main routine. If FBSRCH was the calling routine, all output other than error messages and the value of the objective function is suppressed until the search for the optimal values of the control variables is complete.

MODEL APPLICATIONS

The distribution/utilization system cost analysis model may be used to explore the relative economic effectiveness of alternate strategies for reducing energy losses. These strategies may require capital investment and/or change in operating or planning policy.

Examples below demonstrate the model's evaluation of higher primary and secondary voltages which have the effect of reducing current levels and thus losses. Larger conductors are also considered as a means of reducing losses. Improvements in transformer materials and design may reduce fixed core losses. The extent to which a consequent increase in transformer cost can be absorbed and remain economic is easily estimated by the model.

Fixed core losses increase with transformer rating. Copper losses increase with the square of the transformer load. The model can search for the optimal policy for initially sizing a distribution transformer as well as for replacing it with a larger transformer. More frequent changeout is likely to be justified with higher energy costs.

The effects of load management on distribution system and end-user costs can be explored. In this case, however, the savings in distribution system losses due to reduced peak demand need not entirely offset the costs of load control, as there may be significant savings in the bulk power system.

More precise regulation of service voltage may result in more efficient operation of the customer's appliances. As a consequence, the customer's energy usage may decrease. The charges for capital and O&M as well as the costs of losses associated with the distribution system that provides the regulated voltage will contribute to the utility's revenue requirement. The model may be used to find the limits on regulation that would minimize the end-user's electric bill.

Other uses of the model include exploration of the costs of alternate allocations of voltage drop across the different portions of the distribution system, alternate applications of shunt capacitors for power factor correction and different ways of regulating circuit voltage.

Examples

Three applications of the model are presented. In all three an aerial residential distribution system is modeled over 30 years. The initial load density is 1 MVA/sq. mi. growing linearly to a density of 5 MVA/sq. mi. in year-30. The costs given as output are present worth of all costs incurred over the study period and are expressed in 1979 dollars per square mile served. The nominal charge for losses is \$30/kW for capacity and \$.04/kWh and \$.05/kWh for transformer core and I^2R conductor losses respectively.

Fig. 9. System costs as a function of primary voltage.

In the first example, system costs and conductor sizes are observed as primary voltage ranges from 13 kV to 69 kV. The secondary voltage is 120/240V, single-phase. The fully loaded secondary circuit is limited to 16 residences. The results are summarized in Fig. 9.

Optimal conductor sizes remain roughly constant over the range of primary voltages. Minimum total cost occurs near 28 kV. Other computer runs were made with alternate load

densities and development rates and with the cost of energy losses doubled [19].

When load density is reduced to 0.5 MVA/sq. mi. and 1.0 MVA/sq. mi. for years 1 and 30, respectively, the optimal primary voltage increased about 4 percent. When load density is increased to 16 MVA/sq. mi. and 32 MVA/sq. mi. for years 1 and 30, respectively, the optimal primary voltage increases about 35 percent to around 36 kV. The latter increase is even higher when equipment costs for voltages above 34 kV are conservatively reduced to reflect the effect of high production levels.

When per-unit energy costs are doubled, optimal primary voltage increases about 1 percent. Increases in optimal conductor sizes, however, range between 20 and 35 percent. Total cost for the 30-year period increases about 4 percent.

A conclusion that may be drawn from this example is that optimal primary voltage appears to lie between 25 kV and 40 kV for a wide range of load densities and growth scenarios.

The second example is a study of utility and end-user costs over a 30-year period as single-phase secondary voltage is varied between 120/240V and 480/960V. Primary voltage is fixed at 33 kV. The maximum feasible length of secondary circuit is used for each secondary voltage. The end-user costs include the cost of the end-use system, the difference in the cost of end-use devices arising with choice of nominal voltage above 120/240V and the cost of conversion losses in these devices as these losses may vary with nominal voltage.

The results are summarized in Fig. 10. Note that the utility costs reach a minimum with a secondary voltage near 300V. End-user costs, however, increase with voltage to overwhelm any utility savings. Comparing utility costs for the 33 kV-primary/120V-secondary case with the similar case in the first example, note that a considerable savings arises from maximizing the length of the secondary circuit (see Fig. 2). In the second example, the 120V circuit supplies up to 28 residences instead of 16 in the first example.

The third example considers the effect on conductor sizes and utility/end-user costs of increases in the cost of energy losses. A 33 kV primary/120V secondary circuit is considered. System costs and conductor sizes are plotted in Fig. 11 as per-unit energy costs vary. Note that as per-unit costs of losses increase, optimal conductor sizes increase in a manner that keeps the cost of system losses from increasing at as high a rate.

Fig. 10. System costs as a function of secondary voltage.

Fig. 11. System costs and optimal conductor sizes as a function of energy costs.

The above examples were run on an IBM 370/3033. The model requires 236 k-bytes of core and 90 to 180 sec. of CPU time to obtain each optimized data point presented.

CONCLUSIONS AND RECOMMENDATIONS

The principal issue considered by this study is the optimization of primary and secondary distribution and utilization voltages for the supply of residential or light commercial load. To perform this optimization a distribution/utilization system computer model has been constructed and exercised. The principal conclusions resulting from this study are as follows.

It was found that the optimal primary voltage is in the range of 27 to 36 kV for the wide range of load density and growth rates considered in the parametric studies conducted. Higher optimal primary voltages were not observed, mainly because of the higher cost of equipment associated with distribution voltages above 35 kV. Parametric runs conducted assuming reduced cost for dis-

tribution transformers for primary voltages higher than 35 kv (possibly resulting from increased production) resulted in an increase in the optimal primary voltage. In the case considered, an optimal primary voltage of 37.5 kV was found.

The study determined that 120 V is the optimal secondary voltage. It was found that as the secondary/utilization voltage increases above 120 V, the utility system sees a cost saving. This cost saving, however, is more than offset by cost increases incurred by customers. Customer costs associated with higher utilization voltages are significantly affected by equipment costs that rise steeply with utilization voltage and a requirement imposed for ground fault circuit interruption capability on all circuits using voltages above 120 V. These conclusions may be modified somewhat as higher production levels reduce equipment costs.

In consideration of the effects of higher utilization voltage on the efficiency and operation of electric motors, it was found that small electric motors encounter significant problems at voltages above 250 V. In particular, universal motors which are in widespread use in household appliances encounter significant problems at higher voltages and are difficult to build for voltages over 250 V.

Consideration was given to the inclusion of an autotransformer in the utilization system in order to provide convenience outlet voltages in the range of 120 to 250 V. However, due to the cost of the autotransformer and its associated losses, this alternative was found to be uneconomic.

A number of impediments exist to the implementation of higher primary voltages despite the fact that they could be an economic choice. The major impediments include: the cost of changing to a higher primary voltage (such conversion costs are especially high when the proposed primary voltage does not match an existing subtransmission voltage); the cost of equipment, especially distribution transformers for higher primary voltages, due to low production rate; and possible cost penalties associated with investments required to avoid ferroresonance and to maintain the level of service reliability that the customer perceives as consistent with past performance.

Three areas considered in this study remain somewhat unresolved. These relate to the requirements associated with reliability, ferroresonance and distribution automation and control at higher primary voltage levels. In this study provisions were made in the design of the circuit to limit the peak load interrupted with the isolation of a fault to a specified maximum value. It is not clear that maintaining a consistent level of unavailability will be perceived by the customer

as providing a consistent level of service reliability. Precautions were taken in the design-point studies to assure that system configurations would not encourage ferroresonance. However, these steps do not guarantee that the resulting circuit designs will not be subject ferroresonance. More costly steps may have to be taken to correct ferroresonance as it occurs. The extent of such investment has not been explored. Finally, distribution automation and control equipment can significantly improve system performance. Only approximate requirements and costs of this equipment are provided in this study.

The distribution/utilization system cost analysis model is available to the reader [19] upon request. This model is capable of evaluating all costs associated with the development and operation of the distribution system to supply an evolving residential/light commercial load. Its specific intent is to explore and define the areas in which capital investment or change in planning or operating policy have the potential to reduce energy losses sufficiently to yield positive net economic benefit. Specific features of the model are as follows:

- The model is dynamic in that it provides for analysis of the effects of changing load (seasonal and daily load shapes, and peak demand) over an extended study period.
- The model includes the option to consider systems which are all aerial, all underground or any combination of both.
- Cable ratings are a function of peak daily loss factor.
- The model is suited to the consideration of residential and light commercial service areas.
- The model includes the end-user system and can account for capital costs and losses in this system.
- The model computes losses year by year in the system and both the demand and energy components of these loss costs. These include copper, iron and dielectric losses.
- The model accounts for different transformer sizing and change-out policies.
- The model makes use of homogeneity and fullness factors to describe voids in a system and system growth with respect to time in order to obtain proper count of system components, and thus proper representation of system capital and operating and maintenance costs.

- The model is modular and can be easily modified to incorporate different cost functions, to account for different system configurations or to incorporate different system development rules.
- The model provides a capability for optimization of a number of different variables including conductor sizes, transformer sizing and change-out policy.

Typical problems that can be studied using the computer model include the following:

- Studies of load density including an examination of the cost and optimal system design parameters (voltages, conductor sizes, etc.) as a function of load density.
- Examination of the effect of escalating energy and generation-capacity costs on optimal system voltages, conductor sizes, distribution transformer loss ratios, etc.
- Examination of the effect of load growth (or decline), load profile and load diversity on optimal system design; for example, load management or new loads such as electric cars or heat pumps.
- Examination of the effect of equipment cost changes on the optimal system design.

As presently constructed, the limitations and assumptions of the model are as follows:

- The circuit service area is assumed to be rectangular and all conductors are in a grid configuration.
- Whereas the homogeneity and fullness factors adequately account for capital investment and operation and maintenance costs without the need to refer to specific system geometries, precise computation of losses requires specification of system geometry. The model makes a "homogeneous" assumption regarding system development for loss computation. Specifically, the system is assumed to develop with laterals being placed close to the primary feeder and distant from the primary feeder in equal numbers.
- The model is restricted to the consideration of the unit concept governing substation design and sizing.
- The model includes a number of limitations on system design such as: (1) It is assumed that all conductor sizes are uniform for the length of the specific conductor (main, lateral, secondary). In the case of main and laterals this is done to meet reliability requirements by providing load transfer capacity corresponding to current practice. (2) Tradeoffs between capacitor and conductor sizes are limited. (3) Loss computations are based on a single-phase (not a three-phase) load flow model assuming balanced circuit loading.

Despite these limitations and assumptions, the model provides a mathematical and computational framework within which additional factors and considerations can be taken into account.

All costs used in the model are based on currently available equipment whenever possible. In the case of equipment not currently available (such as load break elbows and distribution-class surge arrestors for 69 kV), cost estimates are based upon PECO Engineering Division experience in consultation with vendors.

The following work could be performed as potential extensions to the existing model:

- Examination of the effect on system cost, losses and system design of different voltage control requirements. For example, +0, -5 percent around nominal 120 V as opposed to ± 5 percent.
- Examination of the cost and loss impacts of assigning specific voltage drops to various parts of the system such as main, laterals and secondaries.
- Examination of cost or loss implications on the distribution/utilization system of dispersed generation and storage.
- Extend the model to account for additional component change-outs due to load growth (or decline).
- Refine the model of the distribution transformer to include capital cost as a function of core losses to allow exploration of capital versus loss costs as they affect total system costs.
- Extend the model to provide for nonrectangular system geometries.
- Extend the model to incorporate a conversion cost model into the program code.

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APPENDIX A DETAILED DESCRIPTION OF BACKUP REPORTS

This appendix provides a brief description and table of contents of five detailed backup reports to this final report. These reports are available upon request.

The First Interim Report, "Literature Search and Problem Definition", provides a review of the state-of-the-art of developments in primary and secondary distribution systems, end-use elements, and in economics and systems analysis/optimization relevant to the use of higher distribution and utilization voltages. Consideration is given to equipment for use with primary distribution voltages in the range of 13 to 69 kV, and secondary distribution voltages in the range 120 V to 960 V. This report also identifies the potential advantages and disadvantages of higher distribution and utilization voltages for both the distribution system and the end-use system. Finally, the report provides an annotated bibliography of relevant literature.

Review of the literature indicates that equipment design for application in a 34 kV-class distribution system is well developed. Insulation for 34 kV equipment is designed to withstand a basic impulse level of 125 to 150 kV with a tendency toward the use of 150 kV. An effort to minimize consumer interruption during circuit maintenance has led to the development of inexpensive switches and connectors capable of opening the circuit under loaded conditions. Three-phase switches have been incorporated into distribution transformers to avoid single-pole switching and thus reduce the problem of ferroresonance. Some distribution-class equipment (in particular load-break elbows and surge arresters) for higher voltage classes are found not to exist at the present time.

Many papers are found in literature dealing with the technology and economics of higher distribution voltages. In general, the earlier papers deal with the technology and projected economics and the latter papers, published in the 1970's, discuss the problems and benefits following conversion to higher voltages. Also in the 1970's, with rising energy costs, additional emphasis is placed in the literature on system losses.

The table of contents for this report is shown in Table A.1. The report is dated December 31, 1978.

The Second Interim Report, "Identification of Components and Parameters for Cost and Energy-Efficiency Analysis" identifies potential systems configurations and components which comprise the systems within these configurations. A list of specifications of computer models for component and electric motors is provided.

A principal output of this report is a detailed discussion of electric energy use in the residential and light commercial sectors. Electric motor types and horsepower ranges are identified for various residential applications. Their annual energy consumption efficiency and energy losses are identified. It is shown that the category of use which produces the largest losses is refrigeration. Also shown is the change in energy consumption for the residential sector between the years 1968 and 1975.

Table A.2 provides the table of contents for this interim report. The report is dated March 30, 1979.

The Third Interim Report, "Analysis of Individual Component Cost and/or Energy Efficiencies" provides mathematical models for the components of the distribution and end-use systems and electric motors identified in the Second Interim Report. The models provide data in both graphical and equation form on distribution and utilization system elements, capital costs, operation and maintenance cost and energy losses. The associated tabular data (costs and losses) for distribution components are presented in Appendices A and B of the Fourth Interim Report.

Five types of electric motors, Universal, Shaded Pole, Split Phase, Capacitor and Three-Phase are modeled. Motor models cover the horsepower range from 0.25 HP to 5 HP and data provided include rated line current, locked rotor current, efficiency and power factor as a function of line voltage rating, for line voltages ranging from 115 V to 920 V.

The results provided in this interim report show sharp increases in cost of many currently available distribution system components for voltages above 35 kV. In particular, it is shown that the cost of distribution transformers increases by about a factor of four as one progresses from 35 kV class equipment to 69 kV class equipment. These drastic increases in cost, arising largely from low production rates, strongly affect the economics of higher distribution voltages.

The table of contents for this report is given in Table A.3. The report is dated October 26, 1979.

The Fourth Interim Report, "Assessment of Optimum Distribution Configuration" discusses the distribution/end-use system model and its development, and provides a user guide for the Electric Distribution/Utilization System Cost Analysis Model (EDUSCAM) computer program. This volume also contains a net energy analysis model and provides example cases and a limited number of case studies. A discussion of the design-point studies which form the backbone of the computer model is provided along with detailed descriptions of the distribution circuit components and their associated bills of materials. Appendix D of this volume provides a listing of the EDUSCAM computer program.

The Fourth Interim Report contains a set of parametric studies conducted using the EDUSCAM computer program. These studies illustrate the use of the program and provide insight on the results to be expected. It is shown that, for a wide range of load density and load growth, the optimal primary voltage falls in the range of 27 to 36 kV. Studies conducted using the model verify the optimality of the 120 V secondary voltage.

The table of contents of the Fourth Interim Report is provided in Table A.4. This report is dated August 29, 1980.

The Fifth Interim Report, "Assess Constraints to Higher Voltage Implementation" summarizes problems encountered in, and factors tending to constrain, the implementation of higher distribution and utilization voltages. It provides a discussion of the impact of reduced equipment costs on the optimal choice of primary distribution voltage and provides recommendations for further work.

Included in the Fifth Interim Report is an analysis of the impact of a cost reduction in higher primary voltage distribution transformers. The distribution transformer cost curve was adjusted downward to a level that might be plausible given higher production rates. For the case studied, it was found that optimum primary voltage increased by about 20 percent to 37.5 kV.

The table of contents of this report is given in Table A.5. The report is dated September 5, 1980.

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