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Evaluation of Higher Distribution and/or Utilization Voltages

Second Interim Report (March 1979) Identification of Components and Parameters for Cost and Energy-Efficiency Analysis

Published April 1981

Prepared for:

U.S. Department of Energy

Assistant Secretary for Conservation and Renewable Energy
Division of Electric Energy Systems

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PREFACE

This interim report provides documentation on the second task, Identification of Components and Parameters for Cost and Energy-Efficiency Analysis, of DOE Contract No. ET-78-C-01-2866, Evaluation of Higher Distribution and/or Utilization Voltages. The work performed under this task includes an identification of the elements of the distribution/utilization system, a characterization of the distribution elements and a characterization of end use elements. The purpose of this task is to identify the distribution and utilization system elements which will be subjected to a detailed analysis and computer modeling in later tasks. The elements identified are characterized in terms of their interface with other elements in the system and with respect to their energy consumption, efficiency and costs. A major output of this task is a list of elements to be modeled under Task 3 and a set of specifications for the computer model to be developed under that task.

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1. IDENTIFICATION OF THE ELEMENTS OF THE DISTRIBUTION/UTILIZATION SYSTEM

A system hierarchy has been developed to identify elements of the distribution/utilization system. Subsystems subject to study are identified at the highest level in this hierarchy in Figure 1. The bulk power subsystem and transmission subsystems are not included in this study. The subtransmission subsystem is usually an important consideration in sizing the substation. However, this study will use the unit substation concept, thereby obviating the need to deal with the subtransmission as a part of the overall distribution/utilization system analysis. The remaining subsystems of Figure 1 will be subject to detailed studies. They include substation, primary distribution, distribution transformer, secondary distribution circuit, customer and end use elements. The subsystems shown in Figure 1 are grouped into two categories: the distribution system and the utilization system. The distribution system includes all elements up to but not including the customer's meter. The utilization system begins at the customer's meter and includes the end use elements. The distribution system thus includes substations, primary distribution circuits, distribution transformers and secondary distribution circuits. The utilization system includes the customer and end use elements. The customer's distribution equipment may be further disaggregated into the following elements:

- Meter
- Breakers
- Transformers
- Circuits
- Switches
- Outlets.

The end use elements are broken into two major categories:

- Motor loads
- Nonmotor loads.

FIGURE 1 ARRANGEMENT OF THE DISTRIBUTION/UTILIZATION SYSTEM

This section identifies the elements of the distribution/utilization system according to this hierarchy.

1.1 Distribution System

To facilitate discussion of the configuration of the distribution system and of the components of which it is comprised, the distribution system is treated as the combination of four subsystems. These are (1) the distribution substation, (2) the primary distribution circuit, (3) the distribution transformer and (4) secondary distribution circuit.

The distribution substation interfaces with the bulk power transmission system and the primary distribution circuit. It steps-down transmission voltage to provide regulated primary voltage for the supply of a number of primary circuits, and has the switching capability to limit the adverse effects of circuit faults through rapid and selective circuit isolation. The primary circuit distributes substation capacity at primary voltage to geographically dispersed distribution transformers. The primary circuit usually has switching capability to isolate a

fault and restore service to unfaulted sections in a reasonable period of time. The distribution transformer reduces primary voltage to the utilization level and supplies customer service connections in its vicinity via secondary circuits.

In this study, the substation and its service area are considered the basic entity of the distribution system. Representing the geographical area supplied under normal conditions by a single substation, the substation service area includes all three distribution system subsystems. Since the distribution system is simply a collection of substation service areas, a single service area may be used as the basis for the comparative evaluations of cost and losses (per unit of area supplied) for different voltages, technical and economic conditions.

For the purpose of modeling, three assumptions serve to generalize the nature of the service area. These are:

1. The area is assumed to be composed of a load of uniform characteristics (load density, growth rate and load profile)
2. All customers in the area are provided with electrical service at the same utilization voltage
3. The substation service area is of the shape of a regular polygon--the number of sides are equal to the number of circuits radiating from the centrally-located substation.

The third assumption implies that a circuit supplies a triangular area and, that, as new circuits are added in response to area load growth, the order of the polygon increases while enclosing the same land area, Figure 2.

The general configurations of the three subsystems are now discussed individually. These configurations are chosen consistent with the performance, reliability and economic requirements of existing and anticipated distribution systems.

NOTE: SUBSTATION SERVICE AREA MAINTAINED CONSTANT AS NUMBER OF CIRCUITS INCREASES WITH GROWING AREA LOAD.

FIGURE 2 CHARACTERISTICS OF THE SUBSTATION SERVICE AREA

1.1.1 Distribution Substation

The substation will be modeled according to the unit concept. This concept produces a substation the size of which is governed by coordination of equipment specifications rather than by the characteristics of surrounding load and of the existing bulk transmission system.

The configuration chosen, Figure 3, was selected using the transformers' low-side breakers as the design focal point. Full utilization of the breakers' thermal rating will determine the transformers' MVA rating at each selected voltage. With minimum breaker ratings at 1200 amps, the transformer, for the single main configuration at 13 KV, will be rated 28 MVA. The double main configuration will be rated 55 MVA. Transformer ratings for 34 and 69 KV are listed.

The transformer impedance is then chosen such that the substation can be connected to a zero-impedance source and produce a maximum symmetrical, 3-phase, short-circuit duty of 15,000 amps. The reactive impedance (X) for the

FIGURE 3 UNIT SUBSTATION CONCEPT

13 KV, 28 MVA and 55 MVA transformers are 8 percent and 15 percent, respectively. These impedances permit the substation to be connected to any bulk power transmission source and eliminate costly, inefficient line reactors sometimes necessary to limit available short-circuit current. Impedances for the 34 and 69 KV transformers are also shown in Figure 3.

Since the normal rating of the feeder breaker exceeds the rating of a single circuit, provisions are made to divide the main 1200 amp feeder into a number of circuits with switches of lighter duty to operate in a coordinated scheme with the main feeder breaker as shown in Figure 3.

The unit substation can be engineered to be placed anywhere in the system, independent of bulk transmission system conditions. Equipment can be specified from manufacturers' standard catalogs and coordinated to fully utilize equipment ratings and limit short-circuit duties. The number of units placed to serve an area, and the reach of each unit can vary with the load density and the choice of primary voltage.

Standardization has long been a proven economic advantage in industry. The unit substation concept provides electric utilities "assembly line" advantages in installation of distribution substations. Substation construction costs can be more easily managed through standard labor, land and equipment requirements for the unit substation versus nonstandardized substations, and equipment costs can be lowered by purchasing large-lot quantities. Fewer spare components (transformers, circuit breakers, etc.) are required as back-up for equipment failures. Operating and maintenance costs are lowered through familiarity of equipment and use of specialized test equipment compatible with all substations.

The unit design concept allows the evaluation of the cost of the distribution system to be decoupled from bulk-power transmission facilities. That is, usually the sizing of substations and selection of primary voltage tends to be significantly influenced by existing transmission, which cannot be generalized. The unit design concept, however, provides substation savings to offset the costs of neglecting utility-specific transmission considerations.

With the substation configuration determined, a hypothetical substation can be designed as shown in Figure 4. The substation is shown with outdoor equipment and open bus construction; however, metalclad switchgear would be more advantageous at 13 KV. Metal-clad gear has not been developed for use at 69 KV and at present is cost prohibitive at 34 KV.

FIGURE 4 DISTRIBUTION SUBSTATION

Each element in the substation is now identified and examined for a cost and/or loss dependency on voltage rating. The high-side requirements for the installation are not considered in the substation model.

A. Main Transformer

The main transformer transforms the voltage from the transmission line voltage to the primary distribution voltage level. The transformer includes load tap changers capable of regulating the bus voltage ± 10 percent.

Material and installation costs will increase with increasing distribution system voltages because of higher insulation levels. Since the transformer will reflect a large percentage of the total equipment costs, the substation cost will

have a strong dependency on this component. Losses will increase, for the same reasons, but not appreciably.

B. Surge Arresters

Surge arresters are placed throughout the substation where critical changes in conductor surge impedance occur. They are connected as close as possible to valuable substation components susceptible to damage from voltage surges (for example, transformers, cable terminations, line terminals, etc.). Surge arresters limit lightning and switching voltage surges to levels below the basic impulse level (BIL) of equipment insulation.

The number of surge arresters and installation costs are not expected to increase with increasing voltage. Material costs will increase because of higher insulation levels. There are no losses associated with surge arresters.

C. Current and Potential Transformers

Current and potential transformers are required to monitor current and voltage levels of the bus and outgoing lines. They are also used to provide input to relay protection.

Material costs will increase with increasing voltage levels. Losses are negligible.

D. Main Breaker

The main breaker provides the transformer and transmission line protection and isolation from low voltage bus faults or line faults close to the substation.

Both material and installation costs will increase with increasing voltage. Losses are negligible.

E. Structures

Substation structures are the insulator supports. They must be designed to carry the weight of the bus, insulators and outdoor equipment. The structures must

be capable of withstanding mechanical stress during short circuits or adverse weather conditions.

Material costs will increase with increasing voltages because of higher mechanical strength requirements and larger clearances. No losses are associated with the structures.

F. Insulators

Insulators support the bus and provide electrical insulation between the bus and the structure. They must withstand forces exerted by the bus during short circuits.

Material costs will increase because of larger clearances. Losses are negligible.

G. Bus and Bare Cable

Bus and bare cable are the main current-carrying conductors. Their size must be selected to withstand thermal and mechanical stress during fault conditions.

The installation cost of bus and cable is expected to remain constant with increasing system voltage. There will be a small increase in material costs due to increases in size and quantities needed to accommodate the larger clearances required at higher voltages. Cable losses are expected to be negligible at any voltage because cable is only used for connections between pieces of equipment; therefore, the total number of circuit feet is very small. Bus losses are negligible because mechanical strength requirements dictate bus conductor sizing.

H. Disconnect and Grounding Switches

Disconnect and grounding switches are used to provide a means of electrically isolating a bus section or substation component for maintenance. They are manually operated and have no fault-close or load-drop capability.

Both material and installation costs will increase with increasing system voltages. Losses are negligible.

I. Line Switcher

The line switcher is a motorized circuit switcher used to isolate the line from the bus. This switch will have a full load-drop rating, a limited fault-close rating and no capability for fault interruption.

Both material and installation costs will increase with increasing system voltages. Losses are negligible.

J. Protective Relays

Protective relays detect system faults and provide the appropriate control signals to substation breakers and/or circuit sectionalizers to isolate the fault and to minimize the extent of the disturbance. In general, relay protection complexity and consequently material and installation costs increase with system voltage.

A summary of the voltage dependence of the cost of and losses in substation components is presented in Table 1.

1.1.2 Primary and Secondary Distribution Circuits

In this study, the primary distribution circuit is assumed to be radial and supplies a triangular geographical area. It consists of a three-phase main which bisects the triangular area and single- or three-phase laterals which emanate from the main as shown in Figure 2. The circuit main is capable of division into sections through switching. To provide load-transfer capability, the main is connected to a main from an adjacent substation through an open switch at the periphery of the service area. Some of the laterals will be connected through open switches to laterals of adjacent circuits originating from the same substation. The number and type of sectionizing and transfer switches depends on reliability considerations.

Three primary circuits designs are to be modeled:

TABLE 1 VOLTAGE DEPENDENCY OF ELEMENTS: DISTRIBUTION SUBSTATION		
COMPONENT	DEPENDENCE ON VOLTAGE	
	COST	LOSSES
BUS & BARE CABLE	X	—
STRUCTURES	X	—
INSULATORS	X	—
CIRCUIT BREAKERS	XX	—
DISCONNECTING SWITCHES	X	—
LOAD-INTERRUPTERS	X	—
TRANSFORMERS (LTC)	XX	X
SURGE ARRESTERS	X	—
PROTECTIVE RELAYS	X	—
— NO DEPENDENCY X DEPENDENCY XX STRONG DEPENDENCY		

1. All underground
2. All aerial
3. Aerial primary main with underground laterals and secondaries.

The secondary distribution circuit, like the primary circuit, is of radial configuration. The distribution transformer interfaces the primary and secondary circuits by reducing primary voltage to utilization voltage. The secondary circuit originates from the distribution transformer and feeds customer service connections (connecting to the customer's meter) in the vicinity of the transformer. The secondary circuit and customer service connection are either aerial or underground, corresponding with the nature of the primary laterals.

Single-phase supplies to the customer, with one exception considered here, require three wires. Some provide dual voltages, a higher voltage for larger stationary motor loads and a lower voltage for convenience outlets. Others provide only a higher voltage and require customer transformation on his premises to supply convenience outlets. Three-phase supply to the customer requires four wires and may also require that the customer provide a transformer for lower-voltage convenience outlets.

The type of supply to the customer influences the design of the distribution transformer and the number of conductors in the secondary circuit and service connection. This topic is discussed further below.

The components of the primary and secondary distribution circuits are now described and characterized in the order that they appear in the illustrations of Figures 5 through 8.

A. Conduit

Conduit provides mechanical support and protection to underground primary cable, Figure 5. Since cable insulation thickness increases with voltage, larger conduit or redundant conduit may be required with higher voltages. Material and installation costs will increase moderately if multiple ducts are required per circuit.

B. Manholes or Splice Boxes

Manholes and splice boxes provide space for splicing and/or installation of underground primary cable, Figure 5. Cable diameter and splice-length increases required by increased insulation levels require larger manholes and splice boxes. Consequently, material requirements and costs as well as installation costs will increase with voltage rating.

FIGURE 5 PRIMARY DISTRIBUTION CIRCUIT: SUBSTATION--PRIMARY RISER POLE

FIGURE 6 AERIAL PRIMARY DISTRIBUTION CIRCUIT: OVERHEAD PRIMARY

FIGURE 7 SECONDARY UNDERGROUND DISTRIBUTION CIRCUIT

FIGURE 8 SECONDARY AREIAL DISTRIBUTION CIRCUIT

C. Underground Primary Cable

Underground primary cable provides means for transfer of electrical energy between substation and overhead portion of the primary distribution circuit or other portions of the primary circuit where subsurface construction is desired or required, Figure 5. On a common conductor-size and load-served basis, the material requirements, material costs and installation costs of underground primary cable are expected to increase significantly with increasing voltage because of increasing insulation levels. Conductor losses may decrease because of lower currents required to serve the same load. On the other hand, conductor size can be decreased with increasing voltage, thereby offsetting some reduction in losses. Cable charging currents will increase with increasing system voltage levels and will thereby increase the supply of system reactive power.

D. Riser Pole

The riser pole provides transition between underground and overhead portions of the primary distribution circuit. They also provide a means of disconnecting the underground portion from the overhead portion. The riser pole consists of a supporting structure, cable terminator(s), disconnect(s), switch(es) or cutout(s), and surge arrester(s), Figures 5 and 7. Increased insulation levels required by increased system voltage levels necessitate larger conductor spacings. Consequently, material requirements and costs for poles and fixtures are anticipated to increase with the system voltage level. Negligible increases in material requirements, material costs and installation costs for hardware are expected with increased system voltage levels. Material requirements and costs for insulators are expected to increase with system voltage level because of increased insulation level requirements. Installation costs should remain constant.

E. Cable Terminator

The cable terminator provides a transition between insulated cable used in the underground portion and uninsulated conductor used in the overhead portion. It may also provide transition between insulated cable and equipment, Figures 5, 6 and 7. Increased insulation levels required by higher voltages will require larger terminators; consequently, increased material requirements, material costs and installation costs are expected.

F. Disconnect, Switch or Cutout

The disconnect, switch or cutout provides a means of manually disconnecting portions of the circuit or disconnecting equipment from the circuit. Cutouts may incorporate fuses which will automatically disconnect if an overcurrent situation is sensed, Figures 5, 6 and 7. The material requirements and costs of this component will increase significantly with increased system voltage levels because of increased insulation requirements. Installation costs are also expected to increase.

G. Surge Arrester

Surge arresters provide electrical protection to other components from voltage surges that exceed the insulation capabilities of the components, Figures 5, 6 and 7. Material costs will increase with system voltage due to higher insulation levels.

H. Overhead Primary Conductor

Overhead primary conductor provides the means for transfer of electrical energy on the overhead portion of the primary distribution circuit, Figures 5, 6 and 7. On a common-wire-size and load-served basis, the material requirements, material costs and installation costs are expected to remain constant with increases in system voltage level. Conductor losses would decrease significantly because of lower currents required to serve the same load. However, wire size

may be reduced to take advantage of reduced current levels with higher voltages. This would reduce material costs and increase losses over what they would be on a common-wire-size basis although, overall, losses may still be reduced.

I. Sectionalizer

The sectionalizer provides a means of automatically disconnecting a portion of the circuit if an overcurrent followed by a no-voltage situation is sensed. Reconnection is by manual means, Figure 6. Costs increase for the same reasons as given above under F.

J. Recloser

The recloser provides a means of automatically disconnecting portions of the circuit if an overcurrent situation is sensed. A recloser has the capability to automatically reconnect if the cause of the overcurrent is removed within a specified time; otherwise, reconnection is by manual means, Figure 6. Costs increase for the same reasons as given above under F.

K. Capacitor

Capacitors provide power factor correction which has the effect of reducing voltage drop and losses. Capacitor costs increase for the same reasons as given above under F.

L. Transformer

The transformer provides for transformation of electrical energy from the primary voltage level to the secondary voltage level. The transformer may be mounted overhead on a supporting structure or mounted at ground level, Figures 6 and 7. Transformation equipment material requirements, material and installation costs are anticipated to increase with system voltage levels due to higher insulation levels. Energy losses are also expected to increase for the same reason if transformer capacity rating is held constant.

M. Secondary Conductors

The secondary conductors provide for the transfer of electrical energy from the transformer to the secondary service conductors. These conductors may be overhead or underground, Figures 6, 7 and 8. Costs and losses vary similar to Item H.

N. Secondary Service Conductors

Secondary service conductors provide for the transfer of electrical energy from the secondary conductors to the customer. They may be overhead or underground, Figures 7 and 8. Costs and losses vary similar to Item H.

The dependencies of costs and losses on voltage in the various components of the distribution circuit are summarized in Table 2.

1.2 Utilization System

The utilization system is defined to begin at the customer's meter. The meter, therefore, is the interface between the distribution system and the utilization system. Five basic systems, as shown in Figure 9, are considered. Figure 9(a) is a single-phase, three-wire grounded system with equal voltages to ground. The voltage range under consideration for this system is 120/240V to 250/500V. The system is limited to 500V because of the need to supply electricity to convenience outlets at 250V or less. Figure 9(b) is a single-phase, three-wire grounded system but with unequal voltages to ground. This system provides a low voltage, in the range of 120V to 250V, and a high voltage from 240V to 960V. At 960V, the high voltage lead is at a voltage of 840V to ground. This system provides a higher voltage capability while maintaining a low voltage capability. Figure 9(c) is a single-phase, three-wire grounded system with a voltage of up to 480V to ground. Lower voltages are obtained for convenience outlets by the use of a customer-owned autotransformer. This system has the principal advantage that

TABLE 2 VOLTAGE DEPENDENCY OF COMPONENTS: PRIMARY AND SECONDARY DISTRIBUTION CIRCUITS		
COMPONENT	DEPENDENCE ON VOLTAGE	
	COST	LOSSES
PRIMARY CIRCUIT:		
CABLE AND TERMINATORS	XX*	X*
CONDUIT, MANHOLES, VAULTS	X	—
WIRE AND CONNECTORS	X*	X*
RECLOSERS AND SECTIONALIZERS	XX	—
DISCONNECTS, SWITCHES, CUTOUTS	X	—
TRANSFORMERS	XX	XX
SURGE ARRESTERS	XX	—
CAPACITORS	XX	—
SECONDARY CIRCUIT:		
CABLE	XX*	X*
WIRE AND CONNECTORS	X*	X*
— NO DEPENDENCY X DEPENDENCY XX STRONG DEPENDENCY * IF LOSSES ARE HELD CONSTANT, WIRE AND CABLE SIZE DECREASES PROPORTIONAL TO THE SQUARE OF THE RATIO OF "BEFORE AND AFTER" VOLTAGES. IF WIRE OR CABLE SIZE IS HELD CONSTANT, LOSSES DECREASE PROPORTIONAL TO THE SQUARE OF THE RATIO OF "BEFORE AND AFTER" VOLTAGES. IN GENERAL, BOTH LOSSES AND WIRE OR CABLE SIZE WILL CHANGE WITH VOLTAGE.		

secondary distribution is all at a higher voltage, thus increasing secondary reach and improving load diversity on the secondary transformer. Only a fraction of the total power would be transformed to the lower voltage, thereby keeping the autotransformer losses low. Figure 9(d) is a single-phase, two-wire grounded system with a customer-owned autotransformer to provide low voltage for convenience outlets. All secondary distribution in this system is at the higher voltage and further savings are achieved by eliminating the third wire of a three-wire system.

FIGURE 9 RESIDENTIAL AND LIGHT COMMERCIAL DISTRIBUTION/UTILIZATION SYSTEM INTERFACES

Finally, Figure 9(e) is a three-phase, four wire grounded neutral system with voltages up to 250V to ground or 433V phase-to-phase.

These systems cover a range of possible configurations that provide flexibility in examining the use of higher utilization voltages. They permit the use of higher utilization voltages while maintaining a lower voltage (120-250V) capability for convenience outlets. Throughout Figure 9, the voltages shown are exemplary.

1.2.1 Residential Customer's Distribution Systems

The potential residential customer's distribution systems that result from the meter connections discussed above are shown in Figures 10, 11, 12 and 13.

The configuration shown in Figure 10 represents the present-day system: current at 240V is brought in at the service drop and 120V circuits are obtained between each outside line and ground. This system permits larger appliances to use 240V circuits. Ground fault circuit interruption is in some use at present voltage levels. It is likely to be required at higher voltages. Current 120V branch circuits are rated 15A or 20A. These ratings would drop inversely proportional with voltage. The same is true of the high voltage circuits which are presently rated 20-60A.

In this system, large appliances could be operated at up to 480V and lights and smaller appliances using universal motors, shaded-pole motors, timers, bell transformers and solenoids could be operated on the lower voltage (120-250V). This system enables devices which offer design difficulties at voltages above 250V to be used as they are in many parts of the world other than the United States.

Increasing voltage affects wire sizes, breaker current ratings and switch ratings. Higher voltages lower these ratings but simultaneously require higher insulation levels and, for breakers, a potential requirement to interrupt higher fault currents possible due to higher voltages. At higher voltages, safety outlets may

FIGURE 10 CUSTOMER'S DISTRIBUTION SYSTEM: SINGLE-PHASE, THREE-WIRE, GROUNDED NEUTRAL SYSTEM, EQUAL VOLTAGES TO GROUND

FIGURE 11 CUSTOMER'S DISTRIBUTION SYSTEM: SINGLE-PHASE, THREE-WIRE, GROUND NEUTRAL SYSTEM, UNEQUAL VOLTAGES TO GROUND

FIGURE 12 CUSTOMER'S DISTRIBUTION SYSTEM: SINGLE-PHASE, TWO- OR THREE-WIRE

FIGURE 13 CUSTOMER'S DISTRIBUTION SYSTEM: THREE-PHASE, FOUR-WIRE, GROUNDED NEUTRAL

also be required. Thus, most elements of the customer's distribution system are affected by voltage. Installation and maintenance cost differences are likely to be negligible, however.

Figure 11 shows the customer's distribution system corresponding to Figure 9(b). This system provides high voltages up to 960V for larger appliances while maintaining the use of 120-250V for convenience outlets. The high voltage available for large fixed appliances would minimize current levels and potentially reduce losses. The system components are affected similarly by voltage in this system as in the system of Figure 10.

The configuration shown in Figure 12, corresponding to Figures 9(c) and 9(d), utilizes a higher voltage supply (up to 480/960V) in which the higher voltage (960V) is available to supply large fixed appliances. A lower voltage (120-250V) for lighting and motor-driven appliances is obtained by means of a customer-owned autotransformer. The autotransformer would have a voltage ratio of four (480/120V) or less which is an economical voltage ratio for autotransformers.

The major cost difference in this system is that it includes the customer-owned autotransformer. The customer would also be charged directly for the losses incurred by the autotransformer. There are slight differences between the systems for Figures 9(c) and 9(d). The system of Figure 9(c) has a high voltage-to-ground of 480V compared to 960V for the system of Figure 9(d). Also, the autotransformers are somewhat different for the two systems. Otherwise, however, the utilization systems have similar characteristics.

The final residential system configuration under consideration is shown in Figure 13. This is a three-phase, wye-connected system with a grounded neutral. The system may operate on voltages of 120/208V to 250/433V. This system is economical in terms of conductor size and permits simultaneous use of high and low voltages in a range for which equipment is presently available.

TABLE 3 EFFECTS OF HIGH VOLTAGE ON CUSTOMER COMPONENTS

COMPONENT	COST	LOSSES	REQUIREMENT	REMARKS
METER	—	—	—	
POTENTIAL TRANSFORMER	I	I	X	REQUIRED TO ADAPT HIGHER VOLTAGE TO STANDARD WATT-HOUR METER
CIRCUIT BREAKERS	I,D	—	—	EFFECT NOT OBVIOUS
AUTOTRANSFORMER	I	I	X	REQUIRED TO PROVIDE 120-250V SERVICE WITH SINGLE VOLTAGE SECONDARY
CIRCUITS	D	—	—	
SWITCHES	I,D	—	—	EFFECT NOT OBVIOUS
GROUND-FAULT CIRCUIT INTERRUPTORS	I	—	X	REQUIRED FOR REASONS OF SAFETY
OUTLETS	I	—	X	SAFETY OUTLETS REQUIRED AT HIGHER VOLTAGES
I = INCREASING EFFECT D = DECREASING EFFECT X = NEW REQUIREMENT — = NO EFFECT				

Some additional installation cost, over the present system, both in equipment and labor, is required for the three-phase system. But the requirement for copper and the losses in larger motors are reduced. Thus, energy cost to the customer can be lower.

In summary, Table 3 shows the voltage dependency of the components of the customer's distribution system. Almost all of the components are affected to some extent by higher voltages.

1.2.2 Light Commercial Distribution Systems

A great variety of light commercial distribution systems are possible. Many exist today. Thus, this study will focus on two typical systems, a single-phase system and a three-phase system. Light commercial loads here will include customers such as gift shops, small markets and other isolated businesses. Not

included are large stores, hospitals and large schools and department stores. These customers are presently using higher voltages and three-phase current in systems custom designed to meet their needs. Smaller commercial installations are quite similar to residential systems. The light commercial systems considered here are similar in design to the residential systems, but the loads are somewhat different. Figures 14 and 15 show two typical light commercial system configurations.

The dependency of system components on voltage is the same as for the residential customer as shown in Table 3.

1.2.3 End Use Elements--Residential Sector

The above sections have identified the substation and distribution system configurations that are under consideration in this study. However, higher utilization voltages also affect the end use elements. The end use elements consist of motor loads and nonmotor loads--light bulbs, toasters, hot water heaters, dryers, etc. Both the cost and energy efficiency of many end use elements will be impacted by higher voltages and by, possibly, the use of three-phase current. This is especially true of motors which will comprise the major area of focus on end use elements. The energy efficiency of resistive (nonmotor) end use elements is largely unaffected by voltage although, at higher voltages, insulation could become a factor in cost. The purpose of this section is to determine energy consumption by end use element and to identify the number and types of motors in use.

Electricity use in the residential sector is shown in Figure 16. The data shown in this figure derive from the analysis documented in Appendix A. Of these uses, refrigeration, air conditioning, food freezing and washers are essentially 100 percent motor loads and, to some extent, space heating and clothes drying are motor loads. Thus, motor loads account for about 40 percent of total electrical energy consumption in the residential sector. A breakdown of the motor types,

FIGURE 14 LIGHT COMMERCIAL DISTRIBUTION SYSTEM: SINGLE-PHASE, THREE-WIRE

FIGURE 15 LIGHT COMMERCIAL DISTRIBUTION SYSTEM: THREE-PHASE, FOUR-WIRE, WYE-CONNECTED

FIGURE 16 ELECTRICITY USE IN THE RESIDENTIAL SECTOR, 1975

number in use, their energy consumption, energy efficiency and losses is given in Table 4.

1.2.4 End Use Elements--Commercial Sector

The light commercial sector is difficult to define, as it is a combination of various unrelated activities such as small companies and offices, shops, restaurants, hospitals, schools, theaters, museums and so on. From this list of activities, it is evident that factual information on end uses of electricity is practically impossible to obtain. In fact, the latest figures available on the division of energy use in the commercial sector and published in "Patterns of Energy Consumption in the United States," rely more on deduction than on calculation. For this reason, it is doubtful that greater accuracy or insight would be gained by attempting to update the 1968 figures presented in Figure 17. The latter will therefore serve as a

TABLE 4 MOTOR LOADS IN THE RESIDENTIAL SECTOR

APPLIANCES	TYPE OF MOTOR	HP	AVERAGE ANNUAL CONSUMPTION (KWH)	UNITS IN USE (*)	TOTAL CONSUMPTION (**)	EFFICIENCY (%)	LOSSES (**)
AIR-CONDITIONING							
• ROOM	SHADED POLE*** PERMANENT-SPLIT	1/20-1/4 3/4-1 1/2	1,389	38.4	53.3	30 50	— 26.6
• CENTRAL	SHADED POLE*** CAPACITOR-START 3-PHASE (COMM.)	1/20-1/4 2-5	3,600	13.2	47.7	30 75 85	— 11.9
DISHWASHERS	SPLIT-PHASE	1/6-1/2	363	26.9	9.8	60	3.9
DRYERS	SPLIT-PHASE	1/6-1/2	993	28.2	28.0	60	11.2
FREEZERS	SPLIT-PHASE (RES.) CAPACITOR-START (COMM.)	1/20-1/6	1,405	26.6	37.4	50	18.7
REFRIGERATORS	SPLIT-PHASE (RES.) CAPACITOR-START (COMM.)	1/20-1/6	1,270	72.6	92.2	60	36.9
WASHING MACHINES	SPLIT-PHASE	1/6-1/2	100	50.8	5.1	60	2.0
HEAT PUMPS	CAPACITOR-START 3-PHASE (COMM.)	2-5	N.A.	N.A.	N.A.	75 80	N.A.
N.A. = NOT AVAILABLE.							
* MILLIONS							
** BILLIONS OF KWH							
*** SHADED POLE MOTORS ARE USED FOR CONDENSER FANS							

general guide to the division of electricity use in the commercial sector for the purposes of this study. Air conditioning, refrigeration and water heating are here again identified as among the top end uses of electricity and estimated to account for over 65 percent of total electrical consumption in the commercial sector. The most marked increases have probably taken place in air conditioning and in some of the end uses not individually identified, which include electric heat, lighting and various mechanical drives. It is clear from Figure 17 that motor loads represent well over 50 percent (possibly as much as 75 percent) of the total light commercial load.

SOURCE: PATTERNS OF ENERGY CONSUMPTION
IN THE U.S., OFFICE OF SCIENCE
AND TECHNOLOGY, 1972.

FIGURE 17 ELECTRICITY USE IN THE COMMERCIAL SECTOR, 1968

2. COMPONENT MODELS

Chapter 1 identifies the subsystems and subsystem components which comprise the substation and the primary, secondary and customer's distribution subsystems. It then identifies which of these components are affected by primary or secondary voltages, either in terms of costs or energy loss. In this section, engineering and computer model specifications are developed for each affected component. The model specifications consist of identifying:

1. The subsystem which contains the component
2. The component
3. The function of the component
4. The parameters which are relevant in defining the physical nature, cost and energy efficiency of the component
5. The range of the above parameters over which the model must yield accurate results
6. The required output parameters and their units
7. Relevant comments regarding the system.

These component model specifications represent the starting point in the system modeling process. As such, they are subject to revision. The component model specifications follow.

Subsystem: Substation

Component: Substation transformer

Component Function:

Transforms transmission voltage to primary distribution voltage and regulates primary voltage

Model Input Parameters and Range of Validity:

High-side voltage (fixed at 230 kV)

High-side BIL (fixed at 900 kV)

Low-side voltage (13 kV to 69 kV)

Low-side BIL (95 to 350 kV)

Capacity (25-300 MVA)

Initial peak-load density (0.5 to 50 MVA per square mile)

Load growth rate (specified by year in %)

Load duration curve (normalized by peak demand, specified by year)

Marginal cost curve for electrical energy (mills/kWh as function of generation level, specified by year)

Generation capacity cost (\$/MW, specified by year)

Average lifetime of transformer (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Costs of energy and capacity losses (\$/year by year)

Operation and maintenance costs (\$/year by year)

Fixed energy losses (MW)

Variable energy losses (MWh/year by year)

Peak capacity loss (MW/year)

Comments:

230 kV is selected as a common high-side voltage for all sizes of substation transformers. A common high-side voltage will simplify the transformer cost model without significantly affecting the comparison of alternate primary voltages. The BIL required for 230 kV is 900 kV.

All transformers will be equipped with low-side tap-changers capable of varying transformer turns-ratio under load to regulate the low-side bus voltage.

Because of increased insulation levels with higher voltages, transformer cost will increase with increasing voltage.

Subsystem: Substation and Primary Distribution Circuit

Component: Surge arrester

Component Function:

Limits voltage surges on low-side substation bus or on primary circuit to a magnitude within the basic impulse levels of equipment insulation

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV)

BIL (95 to 350 kV)

Nature of application (substation bus or primary circuit)

Average lifetime (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost of installed surge arrester (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Structural requirement and associated capital costs (levelized \$/year) to support the surge arrester

Comments:

Insulation levels will increase with voltage, so insulation and material costs will increase with voltage.

Losses are negligible.

Subsystem: Substation

Component: Circuit breaker

Component Function:

Interrupts fault currents to localize circuit disturbances

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV)

BIL (95 to 350 kV)

Capacity (1200 amp continuous, 15,000 amp interrupting duty)

Average lifetime of circuit breaker (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year) including relaying and other control costs

Operation and maintenance costs (\$/year by year)

Comments:

Insulation levels will increase with voltage, so insulation and material costs will increase with voltage.

Losses are negligible.

Subsystem: Substation

Components: Miscellaneous substation items -

structures and foundations; station cable, insulators and bus; transmission termination and high-side breaker and surge arresters; and site acquisition and preparation

Component Functions:

Excluding transformer, low-side breaker, surge arrester and relaying, these items comprise the substation designed according to the unit concept

Model Input Parameters and Range of Model Validity:

High-side voltage (fixed at 230 kV)

Low-side voltage (13 to 69 kV)

BIL of high-side transformer windings and breaker (fixed at 900 kV)

Average lifetime substation miscellaneous items

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Comments:

Losses are negligible.

Subsystem: Primary Distribution Circuit

Component: Circuit reclosing and sectionalizing switches

Component Function:

Interrupts load current and limited fault currents. May serve to transfer load from one circuit to another. Capable of operation by supervisory control.

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV)

BIL (95 to 350 kV)

Capacity (100 to 750 amps)

Nature of application (underground or aerial, single- or three-phase)

Average lifetime of switches (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Pole crossarms or vault space and associated capital cost to support or house switches (levelized \$/year)

Comments:

Insulation levels will increase with voltage so insulation and material costs will increase with voltage.

Losses are negligible.

Subsystem: Substation and Primary Distribution Circuit

Component: Current and voltage sensing relays and associated instrument transformers

Component Function:

Control fault interrupting, circuit sectionalizing and load-transfer switches

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV)

BIL (95 to 350 kV)

Nature of application (provides control signal to feeder breaker, circuit sectionalizing switch or recloser, or circuit transfer switch)

Response requirement (seconds)

Average lifetime of relay and associated instrument transformers (years)

Tax life (years)

General corporate finance and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Comments:

Cost of instrument transformers for measuring voltage and current will increase with voltage because of increasing insulation requirements. Relays for fault sensing and isolation in higher voltage circuits may cost more because of performance requirements necessary to limit more quickly the effects of a fault on the more heavily-loaded circuits.

Subsystem: Primary and Secondary Distribution Circuits

Component: Conduit for underground cable

Component Function:

Where multiple circuits are expected to be buried in the same trench, conduit allows cables to be installed as needed. Conduit allows easier repair of faulted sections and provides some degree of protection in the event that the trench is accidentally dug into.

Model Input Parameters and Range of Validity:

Voltage level (13 to 69 kV primary; 120 to 960 V secondary; single- or three-phase)

Nature of application (single- or three-phase; primary or secondary circuits)

Cable size (350 MCM to 1500 MCM aluminum)

Cable BIL (95 to 350 kV)

Average lifetime of conduit under consideration (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost per 100 feet of conduit for a single circuit (levelized \$/year)

Operation and maintenance costs (\$/year by year)

Splice-box, vault and manhole requirements when conduit is used and associated capital cost (levelized \$/year)

Comments:

Insulation levels will increase with voltage, so larger conduit will be required to house the larger cables. Therefore, conduit costs will increase with voltage.

Subsystem: Primary and Secondary Distribution Circuits

Component: Splice box, manhole and vault

Component Function:

To provide space for underground cable splices and junctions, capacitors, switches, fuses or transformers

Model Input Parameters and Range of Validity of Model:

Voltage (13 to 69 kV for primary circuits, 120 to 960 V for secondary circuits)
Nature of application (primary or secondary splice, primary or secondary fuses, capacitors or switches, below a padmount transformer or enclosing the entire transformer)
Number of circuits entering the space
Average lifetime (years)
Tax life (years)
General corporate financial and tax data
Cost of money (%/year)
Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)
Maintenance cost over study period (levelized \$/year)

Comments:

Losses are negligible.

Subsystem: Primary and Secondary Distribution Circuits

Component: Aluminum underground cable

Component Function:

Used in underground primary and secondary distribution circuits, either directly buried or in conduit, to transfer electrical energy from substation to end user

Model Input Parameters and Range of Validity:

Voltage level (13-69 kV primary; 120-960 V secondary; single- or three-phase)
 BIL of insulation (95 to 350 kV primary; 600-4800 V secondary)
 Nature of application (single- or three-phase; primary or secondary circuits, or consumer service connection)
 Cable size (#4 to 1500 MCM)
 Type of burial (conduit or direct burial)
 Length of conductor (feet)
 Initial peak demand per 100 feet (0 to 1000 kVA or a function of distance from supply point)
 Load at end of conductor if not included in load per 100 feet (kVA)
 Load power factor
 Supplementary shunt capacitance per 100 feet (specified in kVARs)
 Load growth rate (specified by year, %)
 Load duration curve (specified by year in normalized form)
 Marginal cost curve for generation (mills/kWh as function of system load level, specified by year)
 Generation capacity cost (\$/MW, specified by year)
 Average lifetime of cable under consideration (years)
 Tax life of cable under consideration (years)
 General corporate financial and tax data
 Cost of money (%/year)
 Study horizon (years)

Model Output Parameters:

Capital cost for length of cable (levelized \$/year)
 Costs of energy and capacity losses (\$/year by year)
 Operation and maintenance costs (\$/year by year)
 Energy loss (MWh/year by year)
 Peak capacity loss (MW/year)
 Voltage drop per 100 feet (%)
 Conduit, splice-box, vault and manhole requirements (per 100 feet) and associated capital cost (levelized \$/year)
 Optimal shunt capacitor requirement (kVAR per 100 feet)

Comments:

Insulation thickness increases with higher voltages. This results in increasing cable cost.

Subsystem: Primary and Secondary Distribution Circuits

Component: Support structures for aerial facilities--poles, crossarms, insulators and associated hardware

Component Function:

Support of aerial facilities which may include primary and secondary circuits, disconnecting switch or sectionalizer, transformer or capacitor bank

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV primary circuit; 120 to 960 V secondary circuit; single- and three-phase)

BIL (95 to 350 V)

Conductor size (#4 to 956 MCM aluminum)

Circuit configuration (single- or three-phase)

Equipment supported other than primary and/or secondary circuits

Average lifetime (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operating and maintenance costs (levelized \$/year)

Comments:

Increased insulation and clearances with higher voltages result in increased costs.

Subsystem: Primary Distribution Circuits

Component: Cable terminator

Component Function:

Transition from underground cable to aerial conductor

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV, single- or three-phase)

BIL of insulation (95 to 350 kV)

Average lifetime of cable terminator (years)

Tax life of cable terminator (years)

Cost of money (%/year)

General corporate financial and tax data

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Comments:

Insulation requirements increase with voltage resulting in increasing costs with higher voltages.

Losses are negligible.

Subsystem: Substation and Primary Distribution Circuits

Component: Disconnecting switches, cutouts and fuse holders

Component Function:

Serves to isolate sections of circuit or equipment for maintenance or repair. Not intended to interrupt load or fault currents

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV)

Area of application (substation, primary or secondary circuit; single- or three-phase)

Average lifetime of switch, cutout or fuseholder

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Pole crossarms or vault space requirement and associated capital cost (levelized \$/year) to support or house the switches

Comments:

Insulation levels will increase with voltage, so insulation and material costs will increase with voltage.

Losses are negligible.

Substation: Primary Distribution Circuits

Component: Overcurrent fuses for distribution circuit

Component Function:

Isolation of faults in primary and secondary distribution circuits

Model Input Parameters and Range of Model Validity:

Voltage 13 to 69 kV for primary circuits, 120-960 V for secondary circuits)

BIL (95 to 350 kV)

Nature of application (aerial or underground, single- or three-phase)

Rating (10 to 100 amps)

Average lifetime of overcurrent fuses (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost which includes replacement cost (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Pole crossarms or vault space requirement and associated capital costs to support or house the fuses (levelized \$/year)

Comments:

Insulation levels increase with voltage resulting in increasing insulation and materials costs.

Losses are negligible.

Subsystem: Primary and Secondary Distribution Circuits

Component: Aluminum overhead wire

Component Function:

Used in aerial primary and secondary distribution circuits to transfer electrical energy from substation to end user

Model Input Parameters and Range of Validity:

Voltage level (13 to 69 kV primary, single- and three-phase circuits; 120 to 960 V for secondary, single- and three-phase circuits and consumer service connections)
BIL (95 to 350 kV)

Wire size (4/0 to 954 MCM for primary circuits, #4 to 954 MCM for secondaries)

Length of conductor (feet)

Initial peak demand per 100 feet (0 to 1000 kVA or a function of distance from supply point, MVA/100 feet)

Supplementary shunt capacitance per 100 feet (specified in kVARs)

Peak demand connected to end point of conductor if not included in load per 100 feet (MVA)

Load power factor

Demand growth rate (%/year, specified by year)

Load duration curve (specified by year in normalized form)

Marginal cost curve for electrical energy (mills/kWh as function of system generation level, specified by year)

Generation capacity cost (\$/MW, specified by year)

Average lifetime of wire (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost for 100 foot length of conductor over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Energy loss (MWh/year by year)

Peak capacity loss (MW by year)

Costs of energy and capacity losses (\$/year by year)

Voltage drop (%/100 feet)

Pole, crossarm and insulator requirements (per 100 feet) and associated capital costs to support conductor (levelized \$/year)

Optimal shunt capacitor requirement (kVAR/100 feet)

Comments:

Insulation levels increase with voltage resulting in requirements for larger insulators and greater clearances. Higher costs per conductor-foot are therefore expected.

Primary conductor sizes smaller than 4/0 are not considered because of insufficient current-carrying capacity and excessive losses. Sizes larger than 954 MCM are not considered because of cumbersome support structure requirements.

Subsystem: Primary Distribution Circuits

Component: Circuit capacitor

Component Function:

Source of reactive power for power factor correction in primary distribution circuits to regulate voltage and to reduce real-power losses

Model Input Parameters and Range of Validity:

Voltage level (13 to 69 kV)

BIL (95 to 350 kV)

Nature of application (underground or aerial, single- or three-phase)

Capacity (.3 to 3 MVAR)

Marginal cost curve for generation (mills/kWh as function of system load level, specified by year)

Generation capacity cost (\$/MW, specified by year)

Average lifetime of capacitor under consideration (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost per MVAR of capacitance (levelized \$/year)

Costs of energy and capacity losses (\$/year by year)

Operation and maintenance costs (\$/year by year)

Fixed capacity loss (MW/MVAR)

Pole crossarms or vault space and associated capital cost (levelized \$/year) to support or house capacitors

Comments:

Insulation levels will increase with voltage, so insulation and material costs will increase with voltage.

Subsystem: Primary Distribution Circuits

Components: Distribution transformer

Component Function:

Transforms primary distribution voltage to utilization voltage to supply secondary distribution circuits

Model Input Parameters and Range of Validity:

Primary voltage (13 to 69 kV, single- or three-phase)
 BIL (95 to 350 kV)
 Utilization voltage (120 to 960 V, single- or three-phase)
 Capacity (25 to 200 kVA for aerial installations, 25 to 500 kVA for underground)
 Nature of application (aerial or underground)
 Initial peak-load density (0.5 to 50 MVA per square mile)
 Load growth rate (specified by year in %)
 Load duration curve (normalized by peak demand, specified by year)
 Load power factor
 Marginal cost curve for electrical energy (mills/kWh as function of system generation level, specified by year)
 Generation capacity cost (\$/MW, specified by year)
 Average lifetime (years)
 Tax life (years)
 General corporate financial and tax data
 Cost of money (%/year)
 Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)
 Costs of energy and capacity losses (levelized \$/year)
 Operation and change-out costs (levelized \$/year)
 Fixed energy losses (MW)
 Variable energy losses (MWh/year by year)
 Peak capacity loss (MW by year)
 Voltage drop through the transformer (%)
 Pole reinforcement or vault space and associated capital cost to support or house transformer (levelized \$/year)

Comments:

These transformers will not have load tap changers, so the voltage drop must be calculated.

Subsystem: Primary Distribution Circuits

Component: Load-break cable terminators

Component Function:

Cable-to-transformer connector capable of removal under loaded conditions

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV primary voltage)

BIL of insulation (95 to 350 kV)

Current-carrying capability (fixed at 200 amps)

Average lifetime of cable terminator (years)

Tax life of cable terminator (years)

Cost of money (%/year)

General corporate financial and tax data

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Comments:

Insulation requirements increase with voltage resulting in increasing costs with higher voltages.

Losses are negligible.

Subsystem: Substation and Primary Distribution Circuits

Component: Communications system for distribution system control and automation

Component Function:

Coordination of switching devices for rapid isolation of faulted circuit section and transfer of isolated unfaulted sections to alternate sources.

Model Input Parameters and Range of Model Validity:

Voltage (13 to 69 kV)

Area peak load density (0.5 to 50 MVA per square mile)

Average lifetime of communications system (years)

Tax life (years)

General financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost over study period (levelized \$/year)

Operation and maintenance costs (levelized \$/year)

Comments:

Costs are likely to increase with voltage because of more complex protection schemes which are necessary to limit the effects of a fault on the more heavily-loaded, higher-voltage, distribution circuit.

Losses are negligible.

Subsystem: Customer's Distribution System

Component: Watthour Meter

Component Function:

Measures energy supplied to the customer for billing purposes

Model Input Parameters and Range of Model Validity:

Customer peak load:

Residential (3,500-15,000 W)

Residential all electric (20,000-30,000 W)

Light commercial (20,000-100,000 W)

Voltage (120-960 V)

Meter configuration (single- or three-phase, number of wires, etc.)

Average lifetime of meter (years)

Tax life (years)

General corporate financial and tax data

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost (levelized \$/year)

Calibration cost (levelized \$/year)

Comments:

The need for instrument transformers must be determined. Instrument transformers will be included as part of the watthour meter. Consider only conventional meter types. Solid-state meters should be excluded from analysis at this time. Energy losses in the meter will be neglected.

Subsystem: Customer's Distribution System

Component: Autotransformer

Component Function:

Supplies power at 120-250 V where only a higher utilization voltage is supplied.

Model Input Parameters and Range of Model Validity:

High-side voltage (240-960 V)

BIL (600-4800 V)

Low-side voltage (120-250 V)

Volt ampere rating (2.5-10 kVA)

Initial peak load (kW)

Load duration curve by installation (normalized by peak load, specified by year)

Load power factor

Marginal cost curve for electrical energy (mills/kWh as a function of system generation level, specified by year)

Generation capacity cost (\$/MW, specified by year)

Average lifetime (years)

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost (levelized \$/year)

Costs of energy and capacity losses (levelized \$/year)

Fixed energy losses (kW)

Variable energy losses (kW/year by year)

Peak capacity loss (kW by year)

Voltage drop through the transformer (%)

Comments:

An autotransformer is required only in installations where secondary service is at voltages entirely above 250 V. One side of the autotransformer must operate at ground potential.

Subsystem: Customer's Distribution System

Components: Circuit breakers and ground fault circuit interrupters (GFCI)

Component Function:

Protection against circuit overload and electric shock

Model Input Parameters and Range of Model Validity:

Current rating (5-60 amp continuous, 5,000-20,000 amp interrupting duty)

Voltage rating (120-960 V)

Speed of operation (1 second for protection, 1 cardiac cycle for safety)

Type (GFCI or standard, single- or three-phase)

Average lifetime (years)

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost (levelized \$/year)

Comments:

GFCI protection will be assumed on all circuits. This requirement is already standard in many countries at higher voltages.

Losses are negligible.

Fault currents presently available in 120/240 V circuits range up to 21,000 amps. The major source of impedance in the system is the substation transformer. At 960 V, the maximum available fault current would be 5,200 amps. However, above about 480 V arcing becomes a problem with circuit breakers. This effect could cause breaker cost to increase significantly at higher voltages.

Subsystem: Customer's Distribution System

Component: Wire

Component Function:

Carry current to end use elements

Model Input Parameters and Range of Validity:

Voltage rating (120-960 V)

BIL (600-4800 V)

Occupied floor space (1200-4500 square feet residential, 600-20,000 square feet light commercial)

Required lighting load (kW)

Number of appliance circuits required

Type of installation (residential, light commercial, all-electric, etc.)

Initial peak load (kW by type of circuit--lighting, appliance, etc.)

Load growth rate (specified by year in %)

Load duration curve (normalized by peak load, specified by year, by type of circuit or major appliance)

Load power factor (by type of circuit or major appliance)

Marginal cost curve for electrical energy (mills/kWh as a function of system generation level, specified by year)

Generation capacity cost (\$/MW, specified by year)

Average lifetime (years)

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost (levelized \$/year)

Energy loss (kWh/year by year)

Peak capacity loss (kW by year)

Costs of energy and capacity losses (\$/year by year)

Voltage drop (%)

Comments:

Insulation levels increase with voltage but wire size decreases. Wire to be sized by current rating according to existing standards.

Subsystem: Customer's Distribution System

Component: Outlets

Component Function:

Provide convenience connections to end use elements

Model Parameters and Range of Validity:

Occupied floor space (1200-4500 square feet residential)

Number of outlets required for light commercial

Current rating (5-20 A)

Voltage rating (120-250 V)

BIL (600-1250 V)

Average lifetime (years)

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost (levelized \$/year)

Comments:

Losses assumed to be negligible. Maintenance assumed to be independent of voltage. Safety outlets may be required at higher voltages.

Subsystem: Customer's Distribution System

Component: Switches

Component Function:

Control current to switched outlets

Model Input Parameters and Range of Validity:

Occupied floor space (1200-4500 square feet residential)
Number of switched circuits for light commercial
Current rating (5-60 A continuous, 5-60 A interrupt duty)
Voltage rating (120-960 V)
BIL (600-4800 V)
Type of circuits (single- or three-phase)
Average lifetime (years)
Cost of money (%/year)
Study horizon (years)

Model Output Parameters:

Capital cost (levelized \$/year)

Comments:

Losses assumed to be negligible. Maintenance assumed to be independent of voltage.

3. ELECTRIC MOTOR MODELING

It is clear from the above analysis that some 50 percent of the total residential and light commercial load is motor load. Both cost and energy efficiency of electric motors depends on voltage. It is thus important to model a variety of electric motors to determine how their cost and energy efficiency depend on voltage, and to determine the effect of the use of three-phase versus single-phase current. Table 5 summarizes the electric motor types and sizes to be studied.

The data to be provided for each motor type, horsepower rating and voltage rating include the following:

1. Capital cost
2. Average lifetime
 - a. Years
 - b. Operating hours
 - c. Starts
3. Efficiency and power factor at rated horsepower and at 0, 25, 50 and 75 percent of rated horsepower for voltages of 120, 180, 250, 400, 600, 800 and 960, or within the specified range.
4. Locked rotor current

From the data generated in this study, a motor model will be developed. A specification for the motor model follows.

TABLE 5 ELECTRIC MOTORS TO BE STUDIED

TYPE	HORSEPOWER RATING	VOLTAGE RATING
SPLIT-PHASE	1/20, 1/12, 1/6, 1/4, 1/2	120-960V
CAPACITOR-START	1/2, 3/4, 1, 1-1/2	120-960V
PERMANENT-SPLIT	1/2, 3/4, 1, 1-1/2, 2, 3, 5	120-960V
SHADED POLE	(SKELETON TYPE AND CASE TYPE--ANALYTICALLY)	
THREE-PHASE	1/2, 3/4, 1, 1-1/2, 2, 3, 5	120-433V
UNIVERSAL	1/20, 1/12, 1/6, 1/4, 1/2, 1	120-250V

Subsystem: End Use Elements

Component: Electric Motors

Component Function:

Convert electrical energy to mechanical energy

Model Input Parameters and Range of Validity:

Motor type (see Table 5)

Horsepower rating (see Table 5)

Voltage (See Table 5)

Nominal load (fraction of rated horsepower)

Marginal cost curve for generation (mills/kWh as a function of system load level, specified by year)

Generation capacity cost (\$/MW, specified by year)

Motor use (hours per year by correspondence to load duration curve)

Motor starts per year

Cost of money (%/year)

Study horizon (years)

Model Output Parameters:

Capital cost (levelized \$/year)

Energy cost (\$/year by year)

Energy loss (kWh/year by year)

APPENDIX A

ANALYSIS OF ELECTRICITY USE IN THE RESIDENTIAL SECTOR

The relative importance of the main end uses of electricity in the residential sector during 1968 are shown in Figure A.1 as percentages of residential consumption of electricity. These figures were derived from the latest available information on total energy consumption in the United States. These estimates have been updated by functional use for 1975. The general methodology used to estimate the number of appliances in use in 1975 was to use the Census of Housing figure as a basis and then add to it a certain percentage of domestic sales during the years 1970-1975, where the remaining sales were taken to be replacements. The appropriate percentage of replacements was estimated according to past trends, market saturation and life expectancy for each appliance. Finally, Edison Electric Institute estimates of typical annual consumption of electricity by each major appliance were used in the computation of the total annual consumption of electricity (in billions of kwh) by functional use.

Table A.1 presents the update of energy consumption for refrigeration. The number of refrigerators in use was computed from the market saturation data in the annual statistical issues of "Merchandising." Although total consumption for refrigeration has increased significantly, its share of the total residential consumption of electricity has decreased. This is due to the extremely high saturation of the refrigeration market (from 99.7 percent to 99.9 percent in the period 1968 to 1975).

The number of electric water heaters in use in 1975 was computed by starting with the 1970 Census of Housing figure and adding 50 percent of electric water heater sales for the subsequent years through 1975, allowing the remaining 50

SOURCE: PATTERNS OF ENERGY CONSUMPTION
IN THE U.S., OFFICE OF SCIENCE
AND TECHNOLOGY, 1972.

FIGURE A.1 ELECTRICITY USE IN THE RESIDENTIAL SECTOR, 1968

TABLE A.1 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR REFRIGERATION			
YEAR	DWELLINGS WITH ELECTRIC REFRIGERATORS (MILLIONS)	AVERAGE ANNUAL CONSUMPTION PER DWELLING (KWH)	TOTAL CONSUMPTION (BILLIONS OF KWH)
1968	57.6	1,270	73.2
1975	72.6*	1,270	92.2
* COMPUTED FROM THE MARKET SATURATION DATA IN THE ANNUAL STATISTICAL ISSUES OF "MERCHANDISING."			

percent to be replacements. The results are presented in Table A.2. Despite a faster rate of growth of electric water heaters, gas water heaters still outnumber electric water heaters, and the total consumption of electricity for water heating has increased just enough to maintain its share of residential consumption.

Electricity as a source for space heating has grown very rapidly, and electric heat is estimated to account for almost 50 percent of installations in all new homes. From Table A.3, it can be seen that 9.2 million homes were electrically heated in 1975, compared with 3.4 million in 1968. This represents an average annual growth rate of almost 25 percent. It is therefore no surprise that the share of space heating in the total residential consumption of electricity has increased significantly, in spite of the decrease in average annual consumption per dwelling for electric heat, which is probably due to newer, better-insulated homes and the use of heat pumps as opposed to resistive heating, as well as to increasing rates and general conservation efforts.

One of the most rapidly growing uses of electricity in households is for air conditioning, and 46 percent of new homes are estimated to be built with central air conditioning. As shown in Table A.4, 13.2 million homes had central air conditioning in 1975 compared to 5.5 million in 1968, and 38.4 million room units were in use as compared to 18.2 million in 1968. This represents an average annual growth rate of about 20 percent. The share of air conditioning in total residential electric energy consumption has therefore increased significantly and is expected to continue to do so, as market saturation for room and central air conditioning is below 40 percent and 20 percent, respectively.

Almost all households own one television set, and a substantial number own two or more. Saturation exceeds 99.9 percent for all sets and is about 75 percent for color sets. The number of televisions in use in 1975 was computed by starting

TABLE A.2 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR WATER HEATING

YEAR	DWELLINGS WITH ELECTRIC WATER HEATERS (MILLIONS)	AVERAGE ANNUAL CONSUMPTION PER DWELLING (KWH)	TOTAL CONSUMPTION (BILLIONS OF KWH)
1968	14.5	4,490	65.4
1975	22.7*	4,800	108.8

* OBTAINED USING 1970 CENSUS OF HOUSING FIGURE AND ADDING 50 PERCENT OF ELECTRIC WATER HEATER SALES FOR YEARS 1970-1975, WHERE THE REMAINING 50 PERCENT WERE ASSUMED TO BE REPLACEMENTS.

TABLE A.3 RESIDENTIAL CONSUMPTION OF ELECTRIC HEAT

YEAR	DWELLINGS WITH ELECTRIC HEAT (THOUSANDS)	AVERAGE ANNUAL CONSUMPTION PER DWELLING (KWH)	TOTAL CONSUMPTION (BILLIONS OF KWH)
1968	3,388	14,153	48.0
1975	9,173*	11,152	102.3

* OBTAINED FROM STATISTICAL ABSTRACT OF THE UNITED STATES, 1977.

TABLE A.4 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR AIR-CONDITIONING

YEAR	UNITS IN USE (MILLIONS)		AVERAGE ANNUAL CONSUMPTION (KWH)		TOTAL CONSUMPTION (BILLIONS OF KWH)		
	ROOM	CENTRAL	ROOM	CENTRAL	ROOM	CENTRAL	BOTH
1968	18.2	5.5	1,375	3,600	25	20	45
1975	38.4*	13.2*	1,389	3,600	53.3	47.7	101

* OBTAINED FROM STATISTICAL ABSTRACT OF THE UNITED STATES, 1977.

with the 1970 Census of Housing figure and adding 60 percent of television sales for the subsequent years through 1975, assuming the remaining 40 percent to be replacements. Some estimates indicate that as much as 55 percent of sales are to replace old sets. The 1975 estimate for television consumption of electricity presented in Table A.5 may therefore be high, all the more so since the average annual consumption may have decreased with the increase in the number of sets per house. The share of televisions in the total residential consumption of electricity has not increased since 1968 and is not expected to do so in the future either, due to its high market saturation.

In 1970, nearly all households were already equipped with ranges. Electric ranges have increased their share from about 45 percent to over 50 percent and this accounts for the slight rise in consumption of electricity for cooking shown in Table A.6. Its share of the total residential consumption has decreased and is expected to continue to do so. Market saturation for ranges is nearly 100 percent. Another important development affecting the downward trend of the amount of electricity used for cooking is the advent of microwave ovens. A study by the American Gas Association shows that microwave ovens use an average of 71.4 percent fewer kwh/year than electric ovens. As prices for microwave ovens become competitive, the share of cooking in the residential use of electricity may be greatly reduced.

The number of home freezers in 1975 was computed by starting with the 1970 Census of Housing figure and adding 70 percent of electric food freezer sales for the subsequent years through 1975, where only 30 percent of sales were allowed to be replacements due to freezers' relatively long life expectancy. As shown in Table A.7, the total consumption of electricity used for food freezing has increased just enough to maintain its share of residential consumption.

TABLE A.5 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR TELEVISION

YEAR	UNITS IN USE (MILLIONS)		AVERAGE ANNUAL CONSUMPTION (KWH)		TOTAL CONSUMPTION (BILLIONS OF KWH)		
	MONOCHROME	COLOR	MONOCHROME	COLOR	MONOCHROME	COLOR	BOTH
1968	82.3	16.8	360	490	29.6	8.2	37.8
1975	107.0*	46.3*	360	490	38.5	22.7	61.2

* OBTAINED USING 1970 CENSUS OF HOUSING FIGURE AND ADDING 60 PERCENT OF THE SALES FOR YEARS 1970-1975, WHERE THE REMAINING 40 PERCENT WERE ASSUMED TO BE REPLACEMENTS.

TABLE A.6 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR COOKING

YEAR	DWELLINGS WITH ELECTRIC RANGES (MILLIONS)	AVERAGE ANNUAL CONSUMPTION PER DWELLING (KWH)	TOTAL CONSUMPTION (BILLIONS OF KWH)
1968	23.6	1,180	28.0
1975	32.5*	1,175	38.2

* OBTAINED USING 1970 CENSUS OF HOUSING FIGURE AND ADDING 40 PERCENT OF ELECTRIC RANGE SALES FOR YEARS 1970-1975, WHERE THE REMAINING 60 PERCENT WERE ASSUMED TO BE REPLACEMENTS.

TABLE A.7 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR FOOD FREEZING

YEAR	DWELLINGS WITH ELECTRIC FOOD FREEZERS (MILLIONS)	AVERAGE ANNUAL CONSUMPTION PER DWELLING (KWH)	TOTAL CONSUMPTION (BILLIONS OF KWH)
1968	16.5	1,405	23.3
1975	26.6*	1,405	37.4

* OBTAINED USING 1970 CENSUS OF HOUSING FIGURE AND ADDING 70 PERCENT OF ELECTRIC FOOD FREEZER SALES FOR YEARS 1970-1975, WHERE THE REMAINING 30 PERCENT WERE ASSUMED TO BE REPLACEMENTS.

The number of electric clothes dryers in home use in 1975 was computed by starting with the 1970 Census of Housing figure and adding 60 percent of electric clothes dryer sales for the years 1970-1975, where the remaining 40 percent were assumed to be replacements. The results are presented in Table A.8. Clothes dryers are somewhat of a luxury item, and it is estimated that only 42 percent of all households were equipped with them in 1975. Most of them were electric. A continued increase can therefore be expected in the use of electricity for clothes drying in the future, but it only represents a small share of total consumption.

Other large appliances include dishwashers and washing machines. As shown in Table A.9, total residential consumption was about 5 billion kwh for clothes washers and 10 billion kwh for dishwashers in 1975. Despite this low level of energy consumption, they are included explicitly because both appliances consume large quantities of hot water, and this indirect use of electricity is included in water heating. Dishwashers, particularly, will increase in relative importance since only an estimated 28 percent of all households are equipped with them. On the other hand, three-quarters of all households have washing machines, and energy consumption for washing clothes increased only to the extent that the number of households and unit consumption increased between 1968 and 1975.

The remaining electric energy used in households was for lighting and miscellaneous small appliances. The amount of electricity used for lighting was calculated assuming that an average five 100 watt bulbs burned four hours per day in each household. The remainder after deducting the consumption for all the major uses in Tables A.1 to A.9 as well as lighting from total consumption of electricity in the residential sector is assigned to miscellaneous small appliances.

The division of the use of electricity in the residential sector is thus updated for 1975, as shown in Figure 16. It must be noted that although the share of

TABLE A.8 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR CLOTHES DRYING

YEAR	DWELLINGS WITH ELECTRIC CLOTHES DRYERS (MILLIONS)	AVERAGE ANNUAL CONSUMPTION PER DWELLING (KWH)	TOTAL CONSUMPTION (BILLIONS OF KWH)
1968	15.2	990	15.1
1975	28.2*	993	28.0
*OBTAINED USING 1970 CENSUS OF HOUSING FIGURE AND ADDING 60 PERCENT OF ELECTRIC CLOTHES DRYER SALES FOR YEARS 1970-1975, WHERE THE REMAINING 40 PERCENT WERE ASSUMED TO BE REPLACEMENTS.			

TABLE A.9 RESIDENTIAL CONSUMPTION OF ELECTRICITY FOR CLOTHES AND DISHWASHING

YEAR	UNITS IN USE (MILLIONS)		AVERAGE ANNUAL CONSUMPTION (KWH)		TOTAL CONSUMPTION (BILLIONS OF KWH)	
	DISH- WASHERS	CLOTHES WASHERS	DISH- WASHERS	CLOTHES WASHERS	DISH- WASHERS	CLOTHES WASHERS
1968	10.9	46.2	360	98	4	5
1975	27.9*	50.8*	363	100	9.8	5.1
*OBTAINED FROM STATISTICAL ABSTRACT OF THE UNITED STATES, 1977.						

electricity used for refrigeration dropped due to a highly-saturated market while that of space heating and air conditioning rose sharply, they still represent the major end uses along with water heating, and together account for over 60 percent of total electric consumption in the residential sector.