Evaluation of Higher Distribution and/or Utilization Voltages

Fifth Interim Report (September 1980) Assess Constraints to Higher Voltage Implementation

MASTER

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Assistant Secretary for Conservation and Renewable Energy

Division of Electric Energy Systems

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PREFACE

This interim report provides documentation on the fifth task, Assess Constraints to Higher Voltage Implementation, of DOE Contract No ET-78-C-01-2866, Evaluation of Higher Distribution and/or Utilization Voltages. The work performed under this task includes the development of a list of impediments to higher voltage implementation including both technological and economic factors, an assessment of the impact of reduced costs for high voltage equipment on the selection of an optimal voltage and a set of recommendations for further work.

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1. CRITICAL COMPONENTS AND CONSIDERATIONS

The analyses performed in the previous tasks of this study examined optimal primary and secondary voltages independent of impediments or constraints which might apply to their implementation. These are considered now.

1.1 Distribution System

1.1.1 Critical Components

All but two components necessary for primary distribution at voltages between 36 kV and 69 kV are currently available. Distribution-class surge arresters and the cable load-break elbows do not exist for voltages greater than 35 kV, principally because there is no demand for such components. A 69 kV load-break elbow designed similar to 13 and 34 kV equipment would be so large as to be physically unmanageable. A new design involving a two-stage disconnecting process might be feasible. The first stage would entail the extraction of a load-breaking central portion; the second stage would then remove the outer-housing and cable from the bushing.

There are several components which contribute to the high costs of primary distribution at voltages above 35 kV. These include distribution transformers, surge arresters, underground cable and conduit, substation load interrupters and disconnecting switches, circuit three-phase switches and capacitors. The estimated costs for these components are based on current production rates and, therefore, rise more steeply as voltage increases above 35 kV. Increased demand for such components would produce cost reductions and thus improve the economics of higher primary voltages. This is illustrated later in this report for the case of distribution transformers.

1.1.2 Special Considerations

A number of special considerations must be given to the conversion to and/or use of higher distribution voltages. These include: cost of conversion, safety, reliability, ferroresonance, aesthetics, fault detection in higher voltage secondaries, equipment availability and financing. These items are now discussed individually.

Cost of Conversion:

A major constraint to the use of higher distribution voltages is the cost of conversion. The cost of conversion, which must be computed separately, must be balanced against any savings that might result from voltage or other system changes. The EDUSCAM program developed under this study provides an estimate of the present worth of system costs, over a planning period of, say, 30 years, referenced to the initial date of system operation. Thus, the cost of system changes should also be computed as a present worth referenced to this date. The cost of conversion is a quantity that can be quite system specific and, thus, somewhat less amenable to general modeling than system costs and losses. However, it is also somewhat easier to compute without computer aids.

The cost of conversion can depend strongly on the extent of the existing subtransmission system which would likely become the basis for the new primary distribution system. In the case of system conversions, the EDUSCAM program finds its best use as an aid in computing system costs and losses for a variety of system alternatives. The better alternatives can then be selected for more detailed analyses, including cost of conversion.

Safety:

There should be no difficulty in developing safe practices for maintenance and repair of the distribution system as primary voltage rises above 35 kV. There

may, however, be some problem with gaining their acceptance by utility personnel. Introduction of a new voltage may require negotiations with maintenance and repair personnel involving the development of new procedures and perhaps a new pay scale. The consequence may be higher maintenance and repair costs.

Reliability:

Another concern is whether or not annual average unavailability is an adequate measure of consistency in reliability of service. Higher capacity circuits accompanying higher voltages will have expanded sectionalization capabilities. These circuits may provide service with an annual availability consistent with their lower voltage counterparts, but may exhibit more frequent (although shorter) interruptions. The customer may perceive such service as less reliable.

If so, steps would have to be taken to limit the extent of short interruptions that arise as a consequence of initial fault-current interruption. This would require coordinated operation of switches capable of interrupting fault currents located out on the circuit. The switches and provision for their coordinated operation, if required, may add considerable cost to the higher voltage circuit.

Ferroresonance:

With higher primary distribution voltages, the probability of ferroresonance increases. A number of design modifications may be made to lessen the chance of its occurrence. Since the approach to the mitigation of ferroresonance is generally experimental (trying the least expensive remedies first), no consideration of possible remedies is considered in the model. If, in practice, the mitigation of ferroresonance requires the more expensive measures, the cost of a higher voltage circuit will increase.

Aesthetics:

It is anticipated that the increase in size of aerial 69 kV facilities over 34 kV will be barely visible to the man-on-the-street. If major resistance to such a change is encountered, however, higher voltage distribution facilities could be forced underground with significant cost penalties. (It should be noted that there is an increasing trend to place residential distribution circuits underground anyway.)

Fault Detection in Higher Voltage Secondaries:

On the secondary it is known that arcing faults can occur at 480 volts and above. These faults may have arc impedances similar to load impedances. In some cases these faults may go undetected and result in fires and equipment damage. The hazard of such faults is a negative influence on the use of higher secondary voltages of 480 V or higher.

Equipment Availability:

If a utility is one of the first to convert to a new, higher voltage, it is possible that the electrical equipment industry may not yet be in a position to offer prices based on mass production. In this case a conversion to a new higher voltage would be more likely to be infeasible.

Financing:

The ability to finance a conversion program may be a major stumbling block to some utilities. A utility operating in an unfavorable regulatory environment may be unable to recoup money spent on conversion intended to achieve long-term savings.

1.2 Utilization System

Impediments to the use of higher voltages in the utilization system include safety, fault detection, wire size limitations, problems with small motors and inertia of the large existing system to serve the present voltage. These items are discussed individually below.

Safety:

As secondary voltage, particularly at convenience outlets, increases above 120 V, there is little doubt that risk of accidents and their consequences both increase. Thus, steps must be taken to minimize risks of higher voltages. One such step that has already been adopted in many countries that use higher secondary voltages is the use of ground fault circuit interruptors. But these add significantly to customer system costs, and they do not provide absolute protection (they only protect against faults to ground).

Additional steps that might be taken to reduce hazards include the use of safety outlets which prevent children from inserting objects into them and enclosing wiring in grounded raceways. Again, these measures increase the cost of the utilization system.

Appliances might also be grounded or double insulated and appliance wire may have to meet certain standards. Safety considerations might dictate the use of heavier wire. These measures further increase customer costs.

Fault Detection:

It was noted in the previous section that at voltages above 480 V it is possible to develop arcing faults which have impedances similar to loads. Such arcs can be difficult to detect, they can occur in end-use devices and they can create added hazards of fire.

Wire Size Limitation:

For purposes of structural integrity, the smallest wire size approved for use in residential construction is #14. At higher voltages, the desired circuit current ratings can be well below the capacity of #14 wire. Thus, wire size and, hence, costs are dictated by structural rather than electrical requirements. This represents a potential cost penalty.

Problems with Small Motors:

As voltage increases, four problems arise for small motors. First, wire size is inversely proportional to voltage, and the number of turns required in field and armature windings is proportional to voltage. For smaller motors this results in increased manufacturing costs and an increased chance of wire breakage, both during construction and operation.

Secondly, the increased number of turns of finer wire with higher insulation requirements increases the space factor, resulting in less conductor area per unit area of winding. This can necessitate larger motor frames, again with increased manufacturing costs and also higher losses, resulting lower operating efficiency.

Third, universal motors, which comprise a major fraction of lightweight appliance motors, develop severe problems with respect to arcing between commutator segments at voltages much above 120 V. For voltages above about 200 V, some form of compensation is required to reduce arcing and, above about 250 V, this measure is no longer adequate. Thus, it is not desirable to operate 60 Hz universal motors at voltages above about 250 V. [Note that many 250 V systems in present use operate at 50 Hz, thereby lessening this problem]. An autotransformer for convenience outlets is necessary for utilization voltages greater than 240 V. This constitutes a significant added expense.

Finally, thermal overload protectors are not presently available for small motors operating at higher voltages.

Inertia:

There presently exists a large industrial infrastructure geared to the manufacture, distribution, sales and maintenance of 120 V, 60 Hz appliances. There would be very substantial costs associated with the creation of a new, higher voltage line in addition to the current 120 V line. Secondly, portability of end-use

devices would diminish with the implementation of higher utilization voltages. These are severe cost penalties which would have to be outweighed by cost advantages due to higher voltages. These cost advantages are mainly realized in the utility system in the form of reduced losses and in increased coverage of the secondary system. Losses in the customer's system occur mainly in the end-use devices. Most conductors, breakers and switches in the utilization system operate at a small fraction of capacity most of the time and, consequently, losses in these system elements are miniscule. As higher secondary voltages diminish these losses somewhat, losses in end-use devices increase, significantly offsetting this gain.

2. EQUIPMENT COST REDUCTIONS

In discussion of the results of the example runs performed under Task IV,* the high cost of 69 kV equipment is suggested as a possible cause for the clustering of optimal primary voltages around the low to mid-30 kV range. The point is made that if the 69 kV costs were lowered (e.g., through the benefits of mass production), the optimal voltages might be higher than those resulting in the example runs.

To examine this, the cost equation of the distribution transformer was altered. The distribution transformer was chosen because its 69 kV costs are much higher than its 13 kV or 34 kV costs and as a result, it makes a significant contribution to total circuit cost at the higher primary voltages.

A cost reduction in the distribution transformer at 69 kV was more or less arbitrarily taken to be one-half of the difference between the existing 69 kV cost and the 69 kV cost estimated with a straight line passing through the 13 kV and 34 kV costs. Only single-phase, 120 volt aerial transformers were considered. The resulting 69 kV cost reductions were 40 percent of the original 69 kV costs. This estimate is in agreement with the expectations of PECO's systems engineering group for mass-produced equipment.

The new 69 kV data and the existing 13 kV and 34 kV data were used to calculate a new regression curve for aerial distribution transformer cost. This equation was then substituted for the existing cost equation in the EDUSCAM program. The new cost equation is:

$$\text{Cost} = \$ (46.04 - 31.18 \times VP + 235.88 \times DTNPR^{1/2} + 0.017 \times VP^3 - 0.001 \times VP \times DTNPR^2 + 0.006 \times DTNPR \times VP^2)$$

* Fourth Interim Report, Assessment of Optimum Distribution Configuration, August 29, 1980.

where VP is primary voltage in phase-to-phase kV and DTNPR equals distribution transformer nameplate rating in kVA. This equation only represented single-phase, 120 volt secondary aerial distribution transformer costs.

After substituting the above cost equation into the EDUSCAM program, the program was used to make an optimization run of primary voltage using the same base data as Case 7 of Tables 5.2 and 5.3 of the Fourth Interim Report. That case has first and final year load densities of 8 MVA/mi² and 16 MVA/mi².

The optimal voltage found for that case is 31.1 kV. When the modified transformer cost equation is used the optimal voltage calculated is 37.5 kV, an increase of over 20 percent. This result supports the notion that as equipment costs are reduced to reflect the effect of mass production of higher voltage equipment, the optimal distribution voltages increase over those resulting in the Task 4 example runs.

3. RECOMMENDATIONS FOR FURTHER WORK

Further work can be fruitfully conducted in two broad activity areas, specific studies making use of the EDUSCAM program and further program development. Specific potential activities are discussed below.

3.1 Specific Studies

Potential specific studies include parametric studies, electric system equipment studies and issue studies.

Parametric Studies:

The EDUSCAM model can be used to parametrically examine the cost impacts of changes in a number of system characteristics, such as:

- Load density—an examination of the cost and optimal system design parameters (voltages, conductor sizes, etc.) as a function of load density.
- Load profile—load profile affects choice of many system components. This study would examine the effect of load profile and load diversity on the optimal system configuration.
- Energy costs—as real energy costs escalate, it becomes increasingly economic to reduce losses. This study could examine the effect of escalating energy costs on optimal system voltages, conductor sizes, distribution transformer loss ratios, etc.
- Load growth—the rate of load growth (or decline) can affect selection of a variety of system parameters. This study would parametrically examine the effect of load growth on a variety of "typical" systems.
- Equipment costs—the cost-optimality of higher distribution voltages depends on the cost of various system components for the higher voltages. This study would determine required cost reductions in components such as the distribution transformer so that various higher distribution voltages become optimal.

Equipment Studies:

Certain system components, especially the distribution transformers, have a major effect on system costs and losses. The models of these components used in

the EDUSCAM program are based on currently available equipment. This study would examine new technologies in certain critical areas. For example, consider the possibility of low loss, high primary voltage distribution transformers. Higher efficiency might be achieved by the use of better core materials or, perhaps, by switched capacity to reduce low-load core loss. The technical capabilities of such technologies and the cost of the resulting components would be determined by means of engineering studies and the economics of such developments would be studied using the EDUSCAM program. This work could be aimed at identifying fruitful areas to devote component development resources.

Problem Area Studies:

The component enumeration and cost models in the EDUSCAM program are based on assumptions regarding reliability and ferroresonance. The resources of this study have been insufficient to fully resolve these issues. For instance, it could be beneficial to consider ferroresonance in more detail as this presently is an area of uncertainty relating to higher voltage implementation that could carry significant cost penalties. Studies in this area would examine specific problem areas in more detail and, based on the results of these studies, modify the EDUSCAM model accordingly.

Issue Studies:

There are many specific economic or cost issues that the EDUSCAM program could be used to study. Among these are:

- The cost or loss implications on the distribution/utilization system of dispersed generation and/or storage or load management.
- The cost implications and effect on optimal system design of the widespread use of electric cars or broader use of heat pumps.
- The cost, losses and system design impacts and requirements of different voltage control requirements, e.g., +0, -5 percent as opposed to ± 5 percent.

- The cost and loss impacts of assigning specific voltage drops to various parts of the system, such as main, laterals and secondaries.

3.2 Program Development

Additional development of the EDUSCAM program could be of value to particular users, especially utilities. Four areas of development are suggested here.

System Configuration:

At the present time the EDUSCAM program models a rectangular distribution area and assumes that all loads are the same. One area of program development would be to relax these assumptions and model a more general system, with more general geometric configurations and less homogeneity in the composition of the load. This would make the program more directly applicable to the requirements of specific utilities.

Conversion Cost Modeling:

It is noted above that a major consideration in the implementation of higher distribution voltages is the cost of conversion. A useful extension of the EDUSCAM program would be to incorporate a conversion cost model into the program code. This would make the program more useful to a utility considering conversion to higher voltages.

Component Changeout:

At the present time, the EDUSCAM program sizes all equipment (except the distribution transformer) to handle at least the maximum load imposed on it during the planning period of interest. Under this effort, additional component changeout logic would be implemented into the EDUSCAM model. This would allow system optimization under the condition that the system evolves over time as loads and other conditions dictate.

Component Modeling:

A refinement of the distribution transformer model to include capital cost as a function of core losses (expressed as a fraction of nameplate rating). This would allow exploration of capital versus loss costs as they affect system costs over a study period.

Other Recommendations for Future Work Include:

Use the capabilities of the ac load-flow model (which is widely exploited in bulk-power system analysis) to explore different schemes for regulating voltage. This would include the use of regulated buses to compute reactive power injection (capacitor) requirements, and the use of automatic adjustment of transformers (tap-changing under load) to explore regulating transformer requirements.

Refine the load model to reflect seasonal variation. This would improve the assessment of load management schemes.