UNITED STATES DEPARTMENT OF AGRICULTURE
Rural Electrification Administration

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SUBJECT: **An Overview of Transmission System Studies**

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PURPOSE: To outline the system studies that should be considered to support design criteria for REA-financed transmission facilities from 34.5 through 765 kilovolts (kV).

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ABBREVIATIONS AND SYMBOLS

1. Abbreviations

AAC - All Aluminum Conductor
ACSR - Aluminum Conductor Steel Reinforced
AN - Audible Noise
ASNR - Ambient Signal-to-Noise Ratio
BIL - Basic Impulse Insulation Level
BSL - Basic Switching Surge Level
CFR - Code of Federal Regulations
EHV - Extra High Voltage
EMI - Electromagnetic Interference
E/M - Electromagnetic
E/S - Electrostatic
HVAC - High Voltage Alternating Current
HVDC - High Voltage Direct Current
kV - Kilovolt
MV - Megavar
MVA - Megavolt-Amperes
MW - Megawatts
NESC - National Electrical Safety Code
OHGW - Overhead Ground Wire
PCB - Power Circuit Breaker
RI - Radio Interference
REA - Rural Electrification Administration
RMS - Root Mean Square
ROW - Right-of-Way
SNR - Signal-to-Noise Ratio
SSR - Subsynchronous Resonance
TNA - Transient Network Analyzer
TVI - Television Interference
UHV - Ultra High Voltage

VAR	- Volt-Ampere Reactive

2. Symbols

D - Rotational mechanical losses
M - Transmission line length
N_1 - Number of turns in transformer primary
N_2 - Number of turns in transformer secondary
P_E - Electrical power
P_M - Mechanical power
P_{max} - Maximum transferred power
r_1 - Winding resistance of primary
r_2 - Winding resistance of secondary
r_m - Magnetizing resistance
R - Series resistance of transmission line
R_A - Armature resistance of generator
R_F - Field resistance of generator
t - Time
T - Developed torque of generator
T_1 - Input torque of prime mover
T_2 - Output torque of shaft load
V - Line-to-line voltage
V_1 - Primary voltage of transformer
V_2 - Secondary voltage of transformer
V_G - Internal voltage of generator
V_M - Internal voltage of motor
V_R - Receiving-end voltage
V_S - Sending-end voltage
V_T - Terminal voltage of generator
L - Radian frequency
X_1 - Leakage reactance of primary
X_2 - Leakage reactance of secondary
X_L - Series reactance of transmission line
X_M - Magnetizing reactance
X_P - Reactance of primary
X_S - Reactance of secondary
X_{SG} - Synchronous reactance of generator
Y_C - Shunt capacitive admittance
Z_L - Series impedance of transmission line
Z_O - Surge impedance
_ - Stability phase angle
$\tilde{O}_G$ - Internal phase angle of generator
$\tilde{O}_M$ - Internal phase angle of motor

1. INTRODUCTION: Recent trends in power system complexity, energy conservation and economic performance of REA-financed projects reinforce the need for careful system planning for transmission facilities. Planning studies generally involve the modeling of these facilities in order that system performance can be conveniently observed and evaluated.

2. PURPOSE: The purpose of this bulletin is to outline the system studies that should be considered to support design criteria for REA-financed transmission facilities from 34.5 through 765 kilovolts (kV).

Presented in Section 3 is a list of transmission system studies for various facility applications that should be considered. Section 4 contains the input data required to perform each study. A flow chart is presented in Section 5 that relates the interdependency of each study to the overall system planning concept. Section 6 contains a detailed explanation of each study.

3. SYSTEM STUDY APPLICABILITY: Table 1 represents a list of the type transmission system studies and requirements to support REA related financing arrangements for projects from 34.5 kV through 765 kV. These system studies should be considered in conjunction with the long range system and financial planning requirements. This list of studies is not necessarily complete nor is it listed in any order of priority. Each study should be completed or considered as required in Table 1 for the specific facility in question in order that system performance can be evaluated. (Refer to Sections 5 and 6 of this bulletin for a detailed description of each study.) The column numbers in the table refer to the following studies:

1) Facility Feasibility
2) Load Flow
3) Reactive Compensation
4) Stability
5) Subsynchronous Resonance
6) Statistical Line Design
7) Short Circuit
8) Insulation Coordination
9) Corona and Radio Interference
10) Electrostatic and Electromagnetic
11) Transmission Facility Economics

Symbols used in Table 1 are defined as follows:

- An "X" indicates study should be performed and submitted to REA in conjunction with a request for REA action on financing arrangements.

- A "Y" indicates study should be performed and submitted to REA with the project design information.
- A "Z" indicates study should be performed but not submitted for review unless requested by REA.

- An "O" indicates it may be advisable to have study performed depending on system complexity. REA should be informed whether or not study will be completed at which time the borrower will be informed if REA desires to review results.

- No mark indicates the study is not generally applicable.

4. INPUT DATA REQUIREMENTS: Prior to developing system models for each planning study, data must be developed: (1) to permit mathematical simulation of the real system, (2) to aid in the analysis of system performance related to equipment performance, and (3) to provide constraints so that system improvements can be made. A brief description of such input data will now be presented for generators, transformers, lines and loads.

4.1 Generators: For steady-state analysis, generators are represented in terms of the real and reactive power to the system. Conversely, for transient performance, system studies may require full representation of the electrical and mechanical characteristics of each generator.

4.2 Transformers: Most system studies require information about core and winding loss resistances, leakage reactances, turns ratios at available taps, and automatic tap-changing limits.

4.3 Transmission Lines: Transmission lines are generally represented by single phase models with equivalent series impedances (resistance-inductance combinations) between line terminals and equivalent shunt admittances at each terminal. For a balanced three-phase transmission system the manner in which a single phase is represented should depend on the line length and accuracy required. In selecting a model, it is usual to classify transmission lines as short, medium, or long. There is no definite length that can be stipulated to divide short and long line analysis. For the majority of the cases, a sufficient degree of accuracy may be obtained by the short line model on lines up to 50 miles (80 kilometers). The degree of accuracy varies with line length and configuration and also with conductor diameter and spacing.

4.4 Loads: In load flow studies, loads are usually represented by constant real and reactive power flow requirements. For stability studies, large motor loads are characterized by induction motor equivalent electrical circuits.

4.5 Miscellaneous: Input data are also developed in order to determine relay settings in terms of loading limits. Transient and dynamic stability studies require knowledge of relay and

TABLE 1 - SYSTEM STUDY APPLICABILITY

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breaker times and operating sequences. Outage rates and durations for all major equipment are also necessary for developing reliability data.

5. SYSTEM STUDY FLOW CHART: The following is a list of system studies that should be considered to support the design criteria along with a system study flow chart that relates each study to the overall planning concept. These studies are listed in Section 3 and are repeated below for convenience:

1) Facility Feasibility
2) Load Flow
3) Reactive Compensation
4) Stability
5) Subsynchronous Resonance (SSR)
6) Statistical Line Design
7) Short Circuit
8) Insulation Coordination
9) Corona and Radio Interference
10) Electrostatic and Electromagnetic
11) Transmission Facility Economics

SSR, item 5, primarily may occur when series compensation is employed. Statistical Line Design Parameters, item 6, are presented in the 1993 edition of the National Electrical Safety Code (NESC) for EHV transmission lines.

A system study flow chart is shown in Figure 1. The facility feasibility study yields information pertaining to voltage level, system capacity, conductor type, and the approximate location of transmission circuits. Once a basic plan is established, a more complete transmission system study is used in order to perform detailed load flow and stability studies. The results of load flow studies help determine the adequacy of the design with regard to acceptable voltage, phase angle, impedance, and power flow variations. Reactive compensation studies utilize information from load flow studies to establish optimum types of reactive (var) sources. Similarly, results from stability studies may show several alternatives to achieve stability before equipment characteristics are specified. After the load flow and stability studies, then possible switching over-voltage problems are investigated via a statistical line design study since these voltages influence line and apparatus insulation levels.

Other statistical line design investigations include lightning, contamination, and flashover strength studies to yield an optimum insulation system for the transmission facility. Short circuit studies are then performed to assure proper selection of protective relays and circuit breaker interrupting characteristics. Similarly, insulation coordination studies are necessary to assure proper protection of facilities against system over-voltage (internal-switching surges and external-lightning strokes).

FIGURE 1 - SYSTEM STUDY FLOW CHART

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Extra-high-voltage (EHV) investigations that concern environmental and safety factors are corona, radio interference, electrostatic (E/S) and electromagnetic (E/M) studies. Finally, transmission facility economic studies should be considered that include tower, conductor, hardware, equipment, and right-of-way trade-off cost analyses.

6. DISCUSSION OF INDIVIDUAL SYSTEM STUDIES: This section gives additional details about each type of study.

6.1 Facility Feasibility: Facility feasibility studies include load and rating requirements, system voltage, surge impedance loading and system capacity.

6.1.1 Load Requirements : The foundation of any system planning study is a determination of the load to be served which should be compatible with an approved Power Requirements Study (7 CFR 1710, Subpart E). This load is viewed in terms of magnitude; daily and seasonal variation; area distribution; behavior characteristics with voltage and frequency variations; and reliability requirements. In addition to requiring full knowledge of the existing load and its characteristics, the planning process calls for the careful projection of load growth. In general, loads are projected for the entire system as well as for each region and each major existing and future substation.

6.1.2 Rating Requirements : Besides their use in operating the system under abnormal conditions, this type of study is essential to the system planning function.

Each type of electrical equipment has a thermal rating which varies as a function of load cycle, ambient, loss of life, sun exposure, etc. Most utilities develop ratings similar to the following:

1) Normal (continuous)
2) Emergency - 4 hours, 8 hours, 24 hours
3) Emergency - 1 month, 6 months

These ratings are used for both planning continuous loads and contingency loads. They also assist in planning for the different equipment loading characteristics in summer and winter.

6.1.3 System Voltage : Transmission system voltages below the extra-high-voltage (EHV) level are between 34.5 and 230 kilovolts (kV). The nominal EHV levels in the United States are 345, 500 and 765 kV.

If a transmission facility is to be developed economically, voltage steps should be neither too large nor too small. In general, a 230 kV transmission system will find it is most economical to stay at 230 kV until load growth requirements dictate 500 kV as a economical level. Similarly, 345 kV systems will probably bypass 500 kV in favor of 765 kV when load growth requirements dictate a higher voltage level.

6.1.4 Surge Impedance Loading : Surge impedance loading (SIL) is a convenient indicator of comparing the approximate load-carrying capability of transmission lines of different voltages. SIL is the load that the line will carry when each phase is terminated in an impedance of:

$$Z_O = \frac{Z_L}{Y_C} \qquad \text{Eq. 1}$$

(formula is squared)

where:

Z_O = surge impedance, in ohms

Z_L = series line impedance, in ohms per unit length

Y_C = shunt line admittance, in ohms per unit length

The SIL, in megawatts (MW), is a function of the magnitude of Z_O (or ${}^{\circ}Z_O{}^{\circ}$) and the square of the voltage as shown in the following equation:

$$SIL = \frac{V^{\text{¨}}}{{}^{\circ}Z_O{}^{\circ}} \qquad \text{Eq. 2}$$

where:

V = root mean squared (RMS) line-to-line voltage, in kilovolts (kV).

While SIL gives a general idea of the relative loading capability of a line, it is usual to load lines less than 300 miles (480 kilometers) above the SIL. Conversely, because of stability limitations, it is usual to load lines greater than 300 miles (480 kilometers) below the SIL unless capacitor compensation is employed. Computer-generated SIL tables of REA transmission structures and lines are presented in REA Bulletin 1724E-201, "Electrical Characteristics of REA AC Transmission Line Designs."

6.1.5 Transmission Line Capacity : The capacity of a transmission line is dependent on the operating voltage, heating limit, economic limit, and stability limit.

6.1.5.1 Heating Limit - Because of power losses, the current flowing in any conductor results in a temperature rise, and if permitted to reach the annealing point, the conductor may be damaged. However, before the annealing point is reached, vertical clearance requirements may be the limiting factor. The load required to create this condition, normally called the heating limit, will vary considerably, depending on the ambient temperature, wind velocity, conductor type and surface condition. (As the heating limit is approached, vertical clearances are generally reduced due to additional sag.) A newly installed aluminum conductor steel reinforced (ACSR) or all aluminum conductor (AAC) has a lower heating limit than a conductor which is weathered and turned dark. The heating limit is not normally a determining factor on long transmission lines unless the conductor is small and loaded beyond the economic limit; on short lines the heating limit is normally reached before the stability limit.

6.1.5.2 Economic Limit - The determination of the most economical conductor size is complex because of the many variables involved. These variables include: (1) rate of load growth, (2) change in geographical distribution and kinds of loads, (3) cost of right-of-way, (4) location of new power supply points, (5) load factor, (6) emergency service, and (7) continuity of service. For system voltages well below the EHV range, conductor sizes can generally be chosen satisfactorily by the application of Kelvin's Law; i.e., the most economical size of conductor is that for which the investment charges are equal to the cost of energy losses.

However, the application of this law to EHV transmission lines will not generally result in the selection of the optimum conductor size. This is because Kelvin's Law does not reflect the change in supporting structures with changes in conductor size, and also does not include the transformer capacity. A complete cost analysis should account for all effects that result from changes in conductor size and circuit loading. These include: (1) total annual fixed cost of the complete transmission line as a function of conductor size, (2) annual cost of power losses, (3) annual cost of reactive (var) supply needed to support the receiving-end voltage, and (4) an annual cost of terminals and transformer capacity required at the sending and receiving ends.

6.1.5.3 Stability Limit - Another factor which may influence line capacity is the stability or power limit. Stability is that attribute of the system which enables it to develop restoring forces equal to or greater than disturbing forces. Steady-state stability is a condition which exists in a power system when there are no sudden disturbances on the system. Transient stability is a condition which exists if, after a sudden disturbance has taken place, the system regains equilibrium. The transient limit is usually lower and of greater importance than the steady-state limit. For relatively long lines, series capacitors or autotransformers may be used to decrease the effective line reactance and therefore increase the stability limit (Section 6.3.1.).

A good "rule of thumb" relationship for obtaining the approximate steady-state capability of a transmission circuit between two terminals is as follows:

$$P_{max} = \frac{0.75\ V^{¨}}{M} \qquad \text{Eq. 3}$$

where:

P_{max} = Maximum transferred power, in megawatts (MW)
V = RMS line-to-line voltage, in kilovolts (kV)
M = Distance between terminals, in miles.

6.2 **Load Flow**: Once facility feasibility studies are performed, a thorough check of the transmission system plan is made with load flow study programs. System planners confirm the adequacy of the proposed transmission network, considering line loadings, bus voltages and reactive (var) supplies. Cases are run as specified by the system planner under normal and outage contingency conditions along with the reliability criteria for each load region. A base case study provides a reference to determine the emergency and future loadings of facilities.

The base case utilizes information corresponding to normal operating conditions. Such a case serves as a comparison to other system conditions that need to be studied. A first contingency case is also recommended since as a general minimum contingency situation, the system should perform with a single facility out of service.

Once a base case is established, one or more changes can be introduced to determine variations in system performance. These changes may include any combination of the following:

a) Take any line or bus out of service;
b) Add loads to any or all buses and lines;
c) Change regulated bus voltages and phase angles;
d) Add or delete new interconnecting lines;
e) Add new generation to any bus;
f) Change transformer taps;
g) Increase conductor size of any line;
h) Control reactive (var) power flow;
i) Increase or decrease transformer capacity;
j) Take any bulk substation transformer out of service.

The performance of the system as indicated by several load flow cases is properly reproduced only within the limits established by the system planner. Each case represents power flows and voltages which would exist on the system if all input data such as loads and generation were precisely reproduced. Although the load flow study results might never duplicate actual system conditions, they are meaningful primarily because the mathematical model can be tested beyond the acceptable performance range of the real system, thus better identifying limiting conditions. An example of a typical digital load flow study is shown in Appendix A.

Load flow programs presently used automatically take into account the voltage regulating capability of synchronous condensers and transformers, while maintaining designated generation schedules as well as net interchange among interconnected systems. Specified changes in system facilities and methods of operation are automatically calculated for a number of cases in sequence.

The required input data for load flow programs generally include: (1) bus designations, (2) line and transformer impedances, (3) real and reactive (var) power flows for each load, (4) generator power output, (5) voltage schedules and reactive (var) power flow limits of generators, synchronous condensers and switched capacitors, (6) tie-line designations, and (7) system interchange information.

Printed output includes the (1) calculated voltage magnitude and phase angle at each bus, (2) transformer, capacitor and reactor data, (3) real and reactive (var) power flows for each line and transformer, (4) net system interchange and tie-line power flows and (5) a record of system changes. Special output features are available or can be developed to aid the planner in the analysis of the system. Examples include lists of facilities loaded beyond preestablished limits, and lists of buses where the voltage is below desirable levels.

6.3 Reactive Compensation: Reactive (var) compensation studies utilize information from load flow studies to establish optimum types and sizes of reactive (var) sources. There are two basic types of system compensation: (1) series compensation, in terms of impedance, is used to reduce a transmission line's effective reactance, and (2) shunt compensation, in terms of reactive power, is used to reduce the magnitude of reactive (var) power that flows in the network.

6.3.1 Series Reactive Compensation: Inductive reactance of transmission lines is one of the most important parameters limiting power flow capability. The insertion of capacitive reactance in series with the line's inductive reactance decreases the line impedance. This helps to increase the transmission system capability requirements. Series compensation effectively increases the transmission line capacity. This reduces the need for higher transmission voltages or greater number of circuits. (When series compensation is used, a subsynchronous resonance (SSR) study should be performed.) When applying series capacitors on EHV systems (345-765 kV), it is important that they do not introduce undue limitations on the flexibility of future system development. The location of series capacitors along the line has a significant effect on the voltage profile, and power losses. For compensation less than 50 percent, it is usually advantageous to locate the capacitors at the midpoint of the line to improve the voltage profile. Unfortunately, this may not be economically practical unless a substation exists near the midpoint of the line.

6.3.2 Shunt Reactive Compensation: As transmission voltages and line lengths increase, the capacitive charging currents from EHV lines also increase. These currents can cause undesirable overvoltages on generators and transformers, as well as increase power losses. In order to reduce the capacitive charging currents, shunt reactors are utilized to minimize the overvoltages during lightly loaded, switching or transient conditions. Shunt reactors may be either switched or directly connected at the transmission line terminals or to the tertiary windings of autotransformers. Tertiary shunt reactors can be switched as system reactive power requirements and voltages vary whereas permanently connected line shunt reactors cannot be separated from the line during switching operations.

6.4 Stability: The starting point of stability studies is the steady-state conditions (determined by the load flow study) immediately before the system disturbance under investigation occurs. Information which can be derived from a steady-state stability study includes the rotor or stability phase angle, real and reactive (var) power flow, bus voltage and system frequency. Transient (first swing) and dynamic (multiple swing) studies are generally performed either on analog devices or a digital computer.

6.4.1 Transient Stability : Generally, a transient stability program utilizes initial voltages and power flows obtained from the load flow program and converts the system to that required for the analysis of transient phenomena. For specified fault conditions and switching operations, the program calculates synchronous and induction machine electrical and mechanical torques, speeds, rotor torque angles, currents, and system voltages. In addition, some programs calculate currents and impedances of selected lines and simulate the automatic operation of impedance-type relays during severe systems oscillations. Switching operations and fault conditions are automatically simulated in sequence to represent the occurrence and clearing of faults.

Input data required depend upon the complexity of the machine representation desired. For the simplest representation, the data required for a synchronous machine is the real and reactive (var) power, stator resistance, transient reactance, and inertia constant. A more detailed representation requires the characteristics of the turbine governor system and generator excitation system, and the detailed reactance, time constants, and magnetic saturation parameters associated with the machine. For most modern studies, the more detailed machine representation is utilized to provide a better understanding of system performance. For an induction machine, the real power, rotor, stator and magnetizing impedances, and the load speed-torque relationships are usually required.

6.4.2 Dynamic Stability : Transient stability studies are generally limited to the analysis of performance within one or two seconds after the fault. It is also important in many cases to simulate subsequent redistribution of power flows according to system inertias and governor characteristics. These dynamic stability conditions generally are important after the sudden loss of large units or generating plants, or a large concentration of load. A number of computer programs for dynamic simulation are available that take into account large system models and accurately represent the dynamic response of loads such as induction motors.

6.4.3 Results From Studies : Transient studies can help determine: (1) need for faster protective relay system, (2) system operating and design weaknesses, (3) desirability of fast valving, and (4) initial heavy loading of key transmission facilities. Dynamic studies generally simulate system performance during the period following sudden loss of generation or load. These studies can aid in system design by determining: (1) high speed excitation performance, (2) effect of load shedding, and (3) potential system cascading effects.

6.4.4 Methods to Improve Stability : Presented below are several methods which may be employed to improve system stability.

a. Conventional Remedies - The most common remedy for improving power-system stability is to speed up the protective system and to increase the amount of transmission capacity. At this point in time, improving relay and breaker clearing times is difficult due to technological and economic considerations (state-of-the-art circuit breakers generally interrupt currents when the ac wave passes through current zero). The time interval between adjacent current zeros on an ac power system is determined by the power-system frequency and generally cannot be changed by the circuit breaker designer. Also, most present day protective relay methods depend on the determination of direction, distance, or impedance parameters that inherently require a certain minimum amount of measurement time for accurate results.

b. Fast Valving - A source of power system instability is the excess energy supplied by the prime mover during the disturbance. If this energy is reduced or made equal to the energy needed by the generator during the disturbance, the generator acceleration problem is also reduced. Valves on modern large generating stations are usually very heavy and if the fast valving process is to be effective, the valve must be operated in a very short time. In several cases, whether the generator will remain stable is determined in less than a second. Thus, the energy input from the turbine must be changed very rapidly.

c. Breaker Selection and Relay Protection - A stuck breaker on a close in three-phase fault may cause loss of synchronism resulting in instability problems. The use of power circuit breakers (PCB), whose poles can be operated individually, is an approach to prevent this condition. If each of the poles can trip independently, there is less probability that more than one of the poles will be stuck. Thus, a three-phase fault can be converted to a single-phase fault in normal relaying time. If the PCB fails to trip because it did not receive the trip signal from protective relays, the preceding method is invalid. For this situation, the installation of the PCB with individual poles will not provide any benefits. The most common method is the use of "stuck breaker" schemes employing overcurrent relays and high speed timers. In this situation the stuck breaker scheme is timed to clear the adjacent breakers within the maximum clearing time. The primary relay scheme must be sped up accordingly.

d. System Damping - System damping is a method of providing restoring forces in order to decrease undesired oscillations or large system swings. Generally, it is difficult to apply fast valving and braking resistors in such a way that there will be negligible system swings after the fault is cleared. In the more usual case where such controls are not used, the swings may be sufficient to cause loss of synchronism after the fault is cleared. Swings that cause loss of synchronism, loss of load, or large voltage excursions, should be controlled to reduce them to acceptable proportions. Damping restores equilibrium between the generator input and output so that minimum power is available for acceleration or deceleration. Two forms of system damping are insertion of a dc tie between two ac lines and load shedding.

A dc tie between two ac lines provides a solution to the stability problem since no phase synchronization exists between the ac lines. The dc tie has characteristics that are suited for the damping function. HVDC controls can be arranged so that the power flow over the dc lines is independent of the conditions existing on the ac lines. Thus, it becomes possible to have the dc tie surge power in accordance with the operating needs of the interconnecting ac systems. Besides high costs, difficulties may be experienced in the practical design of control circuits that develop the intelligence necessary to control the dc line.

Load shedding is another form of system damping. Generally, load shedding relays are installed to disconnect load when there is insufficient generation to maintain normal system frequency. This is a related system problem that is brought about because generator synchronism is lost for other reasons. Voltage reduction is another form of load shedding. This method is complicated by the necessity for extremely high speed underfrequency relays. Because of their sensitivity they often false-trip and cause start-up problems.

6.5 Subsynchronous Resonance: Subsynchronous resonance (SSR) occurs when the natural frequencies associated with the mechanical torques of synchronous machines are close to those imposed by the connecting networks. Steady-state SSR involves spontaneous oscillations that are either sustained or slowly increased in magnitude with time. Transient SSR generally refers to transient torques on the generator shaft resulting from oscillating currents in the electrical network caused by faults or switching operations. The study of SSR requires two phases: (1) stability analysis to insure that oscillations cannot build up during normal operation, and (2) the simulation of switching operations and faults to insure that associated torques do not exceed shaft stress limits. Results from SSR investigations yield the probability of occurrence of SSR in the system. Corrective measures required to reduce SSR are the use of filters to block currents at SSR frequencies and the use of other design techniques besides series compensation to meet system stability requirements.

Transmission systems containing series compensation may exhibit subsynchronous resonance at frequencies below 60 Hz. Thus, currents at subsynchronous frequencies may be amplified by synchronous machines causing undesirable oscillations and potential stability problems. The buildup or decay of these currents is dependent on the series resistance and loading levels of the transmission system.

6.6 Statistical Line Design: The main objectives of overvoltage, short circuit, and insulation coordination investigations are to (1) set criteria for transmission line electrical design, (2) establish ratings of surge arresters and other protective devices, and (3) specify equipment insulation levels. These three investigations will now be discussed.

Line design studies include switching surge evaluations, lightning performance, and contamination and flashover performance. All these factors influence transmission line and apparatus insulation levels. For transmission voltages between 34.5 and 230 kV, line insulation studies may not be necessary if insulation requirements are specified as in REA Bulletin 1724E-200.

6.6.1 Switching Surge Evaluation : One severe overvoltage which the transmission facility must withstand is the switching surge. Switching surges are produced by switching of apparatus such as circuit breakers and disconnecting switches. These overvoltages appear across the line and station insulation, both phase-to-ground and phase-to-phase. Together with lightning and contaminated considerations they determine the required line insulation levels. Switching surge requirements are also used in insulation coordination studies for substation equipment (Section 6.8).

Insulation strength characteristics (which vary with such statistical data as wind, precipitation, and air density) are utilized in the switching surge evaluation. Other factors which affect the insulation system are breaker insertion resistors, line length, configuration, and loading. These parameters determine the waveshape and magnitude of switching surge which, in turn, influence the insulation flashover strength characteristic. Studies on the transient network analyzer (TNA) are an excellent starting point for determination of system insulation based on switching surge performance. These TNA studies may include the following statistical parameter evaluations:

a. Probability of proper circuit breaker operation
b. Probability that an insulator string will swing to a certain position.
c. Probability that weather factors will reduce flashover voltage performance across insulators and gaps.
d. Probability that a voltage surge will exceed the critical flashover voltage rating of an insulator string.

As noted above, switching surge performance is determined primarily by the line insulation. The number of insulators is selected so that the probability of flashover from switching surges does not exceed design specifications. In general, for transmission voltages below EHV (34.5-230 kV), switching surges do not limit the tower insulation design since the insulation strength increases in proportion to the phase-to-structure clearance. At EHV levels (345-765 kV) the air gap begins to saturate and switching surge line performance may become the limiting factor in the choice of tower dimensions and clearances.

6.6.2 Lightning Performance : Besides switching surge studies, a second major consideration in designing transmission lines is lightning performance. Analytically, the lightning problem is extremely complicated being a function of many lightning statistics such as stroke current amplitude, rise times, hit probabilities and frequency of occurrence. (Thunderstorm-day activity is shown on the Isokeraunic map. From the map data, a relative comparison is made of thunderstorm activity in each area.)

Lightning evaluation of transmission facilities includes consideration of storm incidence in the area, tower height and configuration, and insulator string length. Overhead ground wires (OHGW) are usually used to shield phase conductors from direct strokes. The number and location of OHGWs are major factors in estimating the number of shielding failures. In addition to OHGWs, a combination of line insulation and tower footing resistance parameters are used to minimize lightning flashovers across a transmission line.

To obtain an accurate estimate of lightning performance of a proposed line design, transient network analyzers (TNA), digital computers and system modeling methods are employed to determine such parameters as the trip-out rate. Surge arrester ratings for transmission system applications are normally based on data from TNA studies. The resultant transient overvoltages from these studies are statistical in nature and are combined with insulation strength probability studies to estimate lightning flashover performance.

6.6.3 Contamination Performance: The third major line design study is contamination performance of transmission line insulation. Unlike switching surge and lightning studies, which estimate transient performance, contamination studies relate to the 60 Hz or fundamental frequency performance.

Results from contamination studies yield flashover insulation levels of (1) air gaps at extreme swing angles and (2) contaminated insulator strings. Both of these levels are based on statistical parameter such as geographical location and transmission system configuration (such as tower size and geometry).

6.7 Short Circuit: The principal purposes of short circuit studies are listed below:

a. Provide information for proper selection of protective relays to establish system performance requirements and settings.

b. Provide information for proper selection of circuit breaker interrupting requirements.

c. Evaluate voltages during faulted conditions which would affect insulation coordination and the application of surge arresters.

d. Design the type and capability of grounding systems.

e. Establish the electromechanical forces to be withstood by system facilities.

f. Provide data for a variety of network calculations during the process of planning and designing the system.

A variety of computer programs have been developed for performing short circuit studies. Some are designed specifically to facilitate relay studies, while others provide information primarily used in planning. All represent the system by symmetrical component equivalent reactances of various facilities. The programs generally calculate for each bus of a specified system the total three-phase and line-to-ground bus faults, including effects of zero-sequence mutual impedances. Also specified are the three-phase and line-to-ground fault contributions for each line or transformer connected to the faulted bus.

Input data required include bus identification, positive and zero-sequence impedances of lines and transformers, and transient and subtransient reactances of synchronous machines.

The printed output includes all bus faults and line contributions for three-phase and line-to-ground faults for both normal and switched conditions. This allows quick identification of the breaker duties under the worst conditions, and provides data in a form usable for evaluation purposes. In addition, a variety of printouts of currents and voltages can be specified in any combination for every faulted bus.

6.8 Insulation Coordination: Insulation coordination is defined as the protection of electrical systems and apparatus from harmful overvoltages by the correlation of characteristics of protective devices and the equipment being protected.

To coordinate insulation and protective devices, impulse voltage levels are defined in terms of both BIL (basic impulse insulation level) and BSL (basic switching surge level).

The BIL describes the equipment's ability to withstand lightning strokes. Both conventional and probabilistic techniques are employed in investigating the equipment BIL requirements. Factors which affect BIL performance are the magnitude and waveshape of the expected BIL curve along with the probability of occurrence. The standard BIL waveform is 1.2/50 which is a wave that has a front time of 1.2 microseconds and reaches half magnitude (or half crest value) at 50 microseconds (Figure 2). A number of tests may be required to establish BIL such as the (1) front-of-wave test, (2) chopped-wave test, and (3) full-wave test.

Similarly, the BSL describes the equipment's ability to withstand switching surges. The standard BSL waveform is 250/2500 which is a wave that has a front time of 250 microseconds and reaches half magnitude at 2500 microseconds.

Results from insulation coordination studies yield the expected stress requirements on the system equipment. Other outputs include BIL and BSL performance, arrester selection, and system operating constraints for a given or assumed overvoltage, lightning, waveshape and insulation strength characteristics.

FIGURE 2 - TRANSIENT OVERVOLTAGE BIL CURVE

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6.9 Corona and Radio Interference: Radio and television noise or electromagnetic interference (EMI), and audible interference are rapidly becoming controlling factors in the design and planning of transmission systems, especially at EHV and UHV. Two of the most reported environmental effects caused by transmission facilities operating at EHV and UHV (345 kV and above) are corona noise interference and voltage induction. (See Section 6.10)

Electrical discharges due to either corona or gap sparkover are the basic sources of radio and audible noise interference. The pulses caused by these discharges are injected into the transmission line phase conductors or other conducting components which may act as a radiating antenna or transmission media.

Thus, EMI from the transmission lines is caused either by complete electrical discharges across small gaps or by partial electrical discharges such as corona.

Gap-type noise sources can occur in the following transmission line components:

a. Insulators that are dirty, cracked or loose,
b. Splices,
c. Tie wires,
d. Between hardware parts (clamps, brackets, insulator pins, crossarm braces, and guy wires),
e. At small gaps between ground wires and hardware parts,
f. With electrical apparatus that is either defective, damaged, improperly designed, or improperly installed (such as corroded or loose fuse elements, transformer insulation failure, noisy contacts in relays, meters and regulators).

These gap-type noise sources can be located by equipment that traces EMI such as broadcast radio sets and battery operated portable television receivers. Noise sources can be electrically short circuited or minimized by improving the bonding between adjacent conducting parts or by tightening loose connections.

At EHV and UHV corona (an electrical discharge through ionized air) is generally the main source of noise interference. Corona is formed when voltage gradients are above the critical gradient. For a specified operating voltage, conductor contamination is the main cause of corona. However, conductor surface burrs and scratches, and weather (rain, snow, and humidity) cause an increase in corona effects. Other corona byproducts are power loss in conductors and ozone production (a chemical reaction of the corona discharge). Thus, transmission line corona is a source of radio interference (RI) and audible noise (AN) at EHV and UHV. The measure of corona depends on existing ambient conditions prior to line construction and also on the level of noise from the energized line. For RI, the ambient conditions consist of the received signal strength and background noise level. The quality of reception during ambient conditions depends on the ratio of these two components and is called the ambient signal-to-noise ratio (ASNR). RI, resulting from transmission line corona, depends on the ratio of the received signal strength and the noise level produced by the line. This is referred to as the interference signal-to-noise ratio (SNR). The comparison of ASNR and SNR is a measure of the corona produced by a line at any one location. If both the ASNR and SNR levels are high, reception quality will also be high.

6.10 <u>Electrostatic and Electromagnetic</u>: At EHV and UHV the medical and biological concerns due to electric field gradients and the electrostatic (E/S) and electromagnetic (E/M) coupling between overhead transmission lines and conductive objects should be considered.

6.10.1 Medical and Biological: Medical and biological studies deal with the direct physiological effects on humans, animals, and plants subjected to strong electric field. The magnitude of electric field strength (or voltage gradient) at ground level is usually used in medical studies to determine permissible field strength limits for people and animals near energized transmission lines.

6.10.2 Induced Voltage: Electrostatically induced voltages are possible when a conductive object insulated from ground is in the vicinity of alternating current overhead lines. Similarly, electromagnetic induction effects are possible when transmission line phase conductors carrying fault currents cause induced voltages at the open ends of an insufficiently grounded conductive object. If the conductive object is not adequately grounded when a person or animal comes in contact with it, a current flows in the connection to ground through the electrical body resistance. Object ground intervals that will reduce the E/S and E/M induction effects are usually based on the maximum allowable shock current passing through a person or animal when touching the conductive object. For the E/S case, a steady-state shock current magnitude of five milliamperes is considered as the "let-go" level in the 1993 edition of the National Electrical Safety Code (NESC). Other practical considerations may dictate that the shock current magnitude be kept below the one milliampere "threshold of perception" level. For the E/M case, object grounding intervals are based on transient current levels through a person or animal.

Results from E/S and E/M studies help determine the grounding requirements for stationary metallic objects (fences and buildings) and insulated conductive vehicles.

6.11 **Transmission Facility Economics:** The last system study discussed is that of transmission facility economics. Several of the factors that should be considered in an economic study include tower, conductor, accessory, and right-of-way costs. While all these factors enter into a study of transmission costs, two basic elements that are of significant importance are (1) the load-carrying capability of lines in terms of voltage and distance, and (2) the associated equipment, particularly transformers and switchgear. Related to both transmission capability and cost is a third element; an evaluation of the economics of intermediate switching stations. Some of the questions that should be answered in a transmission facility economic study are the following:

a. What diameter of conductor is necessary to reduce radio interference and corona loss to acceptable levels?

b. What line insulation is necessary?

c. What should the BIL of the station equipment be?

d. How much load can be safely associated with a transmission circuit?

e. What is the economic comparison with lower voltage transmission or even high voltage direct current (HVDC) transmission for some installations?

f. What should the electrostatic and electromagnetic requirements be to minimize the effects of voltage induction and field gradients on humans, animals, and plants near overhead lines?

7. CONCLUSIONS: In conclusion, an overview of eleven system studies is presented to support REA-financed transmission facilities from 34.5 to 765 kV. These studies are not necessarily complete nor are they listed in any order of priority. Each study should be considered for the specific facility in question in order that system performance can be observed and evaluated.

DIGITAL LOAD FLOW PROCEDURE AND EXAMPLE

1. Procedure

The general procedure in preparing digital load flow programs includes the following steps:

a. Digital computer solutions follow an iterative process by calculating one of the bus voltages from the estimated values at the other buses for a specified real and reactive (var) power.

b. Each system bus voltage is corrected and the process is repeated until corrections at each bus are less than a specified minimum value.

c. Digital solutions are usually based on node equations. (The digital computer program forms the self and mutual node admittances.)

d. Iterative methods include the Gauss-Seidel Method (also called the method of successive over-relaxation), the Transformer Tap Changing Method, and the Newton-Raphson Method.* Although the third method is more complex than the other two, it has better convergence characteristics and requires fewer iterations.

2. Load Flow Example

Figure A-1 is a one-line diagram of a simple power system with generators connected at buses 1 and 3 and loads at buses 2, 4, and 5. Typical load flow digital computations are presented in Table A-1. The results show the number of each bus, the magnitude and phase angle of each bus voltage and the real and reactive (var) input power supplied by each generator and drawn by each load. Negative values of real and reactive (var) power indicate inductive loads. The mismatch or unbalance in megawatts (MW) at any bus is the difference between the megawatts flowing toward and away from that bus. Mismatch in megavars (MV) is found in a similar manner. The mismatch is an indication of the precision of the results. For example, the megawatt power flow from bus 1 to bus 4 and from bus 4 to bus 1 is 24.81 MW and -23.73 MW respectively, indicating a mismatch of 1.08 MW. Also note that the voltage magnitude at buses 1 and 3 is essentially constant and a worst case voltage regulation of 11 percent occurs between buses 3 and 4.

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*Text, "Elements of Power System Analysis," by Stevenson (Third Edition).

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Figure A-1: One-Line Diagram for Load Flow Study

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Table A-1: Digital Computations for Load Flow Study

TWO-MACHINE STABILITY PROBLEM

The essential factors involved in steady-state stability are illustrated in the following two-machine system (Figure B-1) example.

With reference to Figure B-1, the primary mechanical and electrical parameters affecting steady-state stability are:

1. Mechanical Power (P_M)

   Prime mover input torque (T_1), inertia between prime mover and generator; inertia between motor and shaft load; and shaft load output torque (T_2).

2. Electrical Power (P_E)

   Internal generator voltage (V_G); system network reactance (X_L); internal motor voltage (V_M); stability phase angle (_) by which V_G leads V_M.

The equation relating the real electrical power transfer between the generator and motor is:

$$P_E = \frac{°V_G°°V_M°}{X_L} \sin \_ \qquad \text{Eq. B-1}$$

where $°V_G°$ and $°V_M°$ are voltage magnitudes. If $°V_G°$ and $°V_M°$ and X_L are constant, the electrical power is directly proportional to sin _. This is shown in Figure B-2. Physically, the stability angle is controlled by the relative motion of the rotors of the generator and motor. During normal operation both the rotors and internal voltages rotate at synchronous speed. The angle between V_G and V_M is, therefore, constant. If for any reason the input torque to the generator shaft increases, the generator momentarily speeds up. Thus, the generator rotates at a speed higher than the synchronous speed causing V_G to rotate above the synchronous speed. Since V_M remains at the synchronous speed, the stability angle increases. With reference to Figure B-2, the increase in _ causes more transferred power for _<90°; thus, the system is stable. When _>90°and if the input torque continues to increase, the generator speed and internal voltage increase causing an increase in _. However, the transferred power output decreases since _>90°. In this case the input and output cannot balance and the rotor speed will steadily increase causing the system to lose synchronism and become unstable.

Typical swing angle curves to evaluate transient and dynamic stability performances are shown in Figure B-3 after a sudden disturbance is applied at time t=0. In this case the stability phase angle, _(t), is a function of the system torque, internal voltages, system reactance, and time.

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Figure B-1: Basic Diagram for Two-Machine Stability Problem

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Figure B-2: Steady-State Power Angle Diagram

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Figure B-3: Typical Swing Equation Curves