EQUIPMENT MODELS IN DYNAMIC PERFORMANCE STUDIES

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Detailed equipment models should be used in system performance studies where control effects, stability and damping are significant. Despite the absence of computational limitations, engineers are still tempted to adopt grossly simplified models of certain equipment under the pretext of not having access to the parameters for the more complete models.

PTI's experience indicates that it is far better to use detailed models with assumed typical values of parameters than to characterize the equipment by simplified models which do not represent phenomena pertinent to the study.

A case in point concerns synchronous machine representation. System dynamics studies must recognize the components of torque produced by rotor body and amortisseur winding currents in synchronous machines in the frequency band of rotor angle motion. These effects are associated mainly with the subtransient reactances and time constants of the machines. Hence subtransient effects must be modeled and, most importantly, subtransient data must be provided.

Investigations have confirmed that, while higher order forms are often desirable for machine design work, second order forms for flux dynamics in the d and q axes are adequate for system performance studies.

The most important result of subtransient rotor flux effects is the development of electromagnetic damping torque. This damping effect, which can be characterized in the frequency domain as the coefficient \( \omega_{ab} = \frac{2\pi}{\omega_{d} \omega_{q}} \), can vary widely in strength. In some situations, it is typically several times stronger than the damping contributed by the frequency sensitivity of loads. It is important that the generator modeling include the physical principles of subtransient effects so that their major variations are accounted for, even though refined and exact values for the subtransient parameters may not be available.

To illustrate:

One characterization of the d-axis operational inductance of a machine is given by the expression

\[
L_d(s) = \frac{1}{(1 + \frac{a(L_d/L_d')T_d^\prime s)}(1 + \frac{b(L_d/L_d')T_d^\prime s)}(1 + \frac{a(L_d/L_d')T_d^\prime s)}(1 + \frac{b(L_d/L_d')T_d^\prime s)}
\]

where \( ab = 1.0 \). The expression for \( L_q(s) \) is similar.

While the debate is still on-going as to whether the second order expression above is adequate, or what values should be assigned to \( a \) and \( b \), a common assumption is that \( a \) and \( b \) are unity.

Figure 1 shows the variation of the damping torque coefficient with perturbation frequency for a typical machine connected radially to an infinite bus by a relatively low transmission impedance of 0.25 p.u. and running at full load, with unity power factor. Four cases are shown, as described on page 2.

(continued on page 2)

THE CURRENT STATE OF STATE ESTIMATION: PRACTICAL vs. THEORETICAL CONSIDERATIONS

K. A. Clements
Senior Engineer

The function of state estimation in a power system control center is to convert telemetered network measurement data into accurate, reliable estimates of network bus voltages, real and reactive power flows on transmission lines and through transformers, and real and reactive power injections at network buses. The on-line security monitoring functions which are performed at the control center use the estimates provided by the state estimator. Over the past decade, state estimation has been implemented at several control centers.

The data required by a power system state estimator consists of network data, such as line impedances and substation switch and circuit breaker positions, as well as measurements of such quantities as bus voltage magnitude, real and reactive line flows, and real and reactive power injections at the buses. One point that should be emphasized is that these quantities have not been measured as such in the system. When redundant measurements are available, however, the state estimator is able to utilize them to improve the accuracy of the estimates and to detect faulty measurements as well as errors in network data. This is because the computed state estimate minimizes the differences between the actual measurements and their corresponding values calculated from the estimates. Excessive discrepancies between actual and estimated values indicate the presence of either bad measurements or erroneous network data. This bad data detection capability has proven to be of great value to power system operators and to instrument maintenance personnel.

Least squares analysis, the theoretical basis for state estimation, is a technique that is quite old. As a practical reality, however, power system state estimation is relatively new. Neither sufficient computer capability nor good numerical state estimation algorithms suitable for very large networks have been available until recently.

The first task to be performed in implementing the state estimation function is that of meter placement. It is rarely practical to install sufficient metering throughout the entire network so that all data used in the state estimation process is based on real-time measurements. In addition, the state estimation function is often implemented before all of the planned metering is available. For these reasons, it is necessary to use pseudo measurements at some locations in the network. Pseudo measurements are estimates, usually of bus loads, which are used in place of actual measurement data by the state estimator. Although state estimation can be performed with a measurement set consisting almost entirely of pseudo measurements, its accuracy will not be very good. State estimator accuracy and reliability are dependent on the availability of real-time measurements at certain locations. A meter placement study will reveal those crucial measurements. A common metering system design goal is that state estimation can still be performed when none of the measurements from a Remote Terminal Unit (RTU) are available due to equipment failure. Such RTU's should be identified during the meter placement study and additional metering planned at neighboring RTU's to alleviate this problem. Another design goal is that the measurement system ensure a well-conditioned numerical solution of the estimate. Although little mentioned in the published literature, it has been observed in studies conducted at PTI that both the measurement type and location, as well as measurement and network parameters, can have a profound effect on the numerical behavior of the state estimator. A careful study of these potential problems is advisable during the meter placement study.
Equipment Models (continued from page 1)

(a) Representation of subtransient effects on both axes by the second order expression for \( L_d(s) \) and \( L_q(s) \). Nominal values used for all parameters.

(b) Representation of \( d \)-axis transient effects only by setting

\[
\begin{align*}
I_d'(s) &= \frac{s^{1/2} (L_d'/L_d - \tau_{d0}s)}{L_d(s) (s + \tau_{d0}s)} \\
I_d(s) &= I_d'
\end{align*}
\]

(c) Same as case (a) but with \( T_d'' \) and \( T_q'' \) doubled to show sensitivity.

(d) Same as case (a) but with the parameters \( a = 0.8 \) and \( b = 1.25 \).

> CONVENTIONAL LOAD FLOW AND STABILITY ANALYSIS APPLIED TO THE LONG-TERM SIMULATION PROBLEM

H. K. Clark
Senior Engineer

The design and operation of interconnected systems to limit the frequency and effects of cascading outages has been receiving increased attention in recent years. Computer-program tools are under development to help engineers understand the mechanisms involved, and the design alternatives and strategies that can improve system reliability by reducing susceptibility to cascading outages. The tool that may eventually contribute most in this area is the long-term simulator, if such a tool can be developed to model all relevant effects.

Accurate long-term dynamic simulation will require large quantities of complex computer program, significant computer time, and a full understanding of the complexities of a system under stress. The required data base will include AGC systems, steam generators and associated controls, load shedding and restoration systems, system and plant operator actions, etc. Long-term simulation programs that make use of such data will likely be widely used in the future to design systems with high resistance to cascading. Unfortunately, it is clear that the development of such tools and the required data bases is going to be a slow and tedious process. However, tools are presently available that will allow a skilled engineer with a general knowledge of system operation and equipment to include consideration of cascading resistance in current planning activities.

Sophisticated load flow and stability programs have evolved from many years of development and refinement. They are thought by many to be limited to studies of steady state conditions and transient and dynamic stability, and thus have not been widely applied to the cascading outage question. Some of the more versatile among them can be quite effective in the examination of the effects that must be considered in a long-term simulation.

Conventional studies typically include initial-condition load flows, stability cases, and post-transient load flows. To extend such studies into the long-term realm, load flow cases for several points in time after the initial disturbance are run, with various additional effects included. Any cases showing marginal voltages or severe overloads are augmented with additional load flow cases to better define the condition of the system and the potential failure points that could further degrade or collapse the system. Where stress may result in protective device operation or other events that impose a sudden change in system conditions, a stability run should be made to check transient and dynamic stability. The study of long-term effects using existing programs thus consists of a series of 6 or 8 or more load flow cases interspersed with an occasional brief stability run, and covering 10 to 15 minutes more of system operation following a major disturbance.

The most widely used tool in planning today is the load flow program. A typical load flow solution includes several assumptions:

- All changes in losses and generation-load unbalance will come from remote sources (the swing bus).
- Operators will adjust generator voltage regulators to maintain active loadings within unit continuous capability (var limits are applied).
- Operators or automatic tap controls will move voltage and phase taps to restore the controlled voltage or power (automatic tap changing is invoked).
- Load kW and kVAR will be restored to initial values by inherent load characteristics, or by volt-var control equipment in subtransmission and distribution circuits not represented explicitly in the load flow (loads are constant kVA).

These assumptions lead to a solution that represents a point in time about 5 minutes after a disturbance or system change. Though system stress may be severe at this point in time, there are other effects that should be studied in a complete analysis of the post-transient period. Other effects to be considered include:

- Governor effects.
- Boiler dynamics in units called on for rapid increase in output.
- Manual redispatch of available generation and start-up of standby generation.
- Automatic Generation Control.
- Minimum excitation limiters.
- Automatically controlled shunt capacitors and shunt reactors.
- Load shedding and restoration equipment.
- Operator actions.

(continued on page 3)
THERMO-MECHANICAL BENDING OF PIPE TYPE CABLES

T. Aabo
Senior Engineer

The laminar structure of oil-impregnated paper-insulated cables is largely responsible for the cables' high dielectric strength. As many as 200 individual paper tapes (7/8 inch to 1-1/2 inch wide) are precisely applied in a designed overlay pattern, presenting multiple radial barriers in series with the oil-filled butt spaces. When this overlay pattern is disarrayed significantly, an area of reduced dielectric strength results, characterized by wider than normal butt spaces and higher than normal number of radially aligned butt spaces.

Such an area is known as a "soft-spot" from its spongy feel under finger pressure. More recently, soft-spots have been measured with special hardness testers.

Soft-spots can result from either improper tape application or excessive bending during manufacture, test or installation. Most of the problems related to these operations have been effectively eliminated by application of modern taping theory, practices and equipment, and by rigorous quality control of handling and installation activities.

Over the last several years, another mechanism of soft-spot formation has surfaced in commercial 345 kV cables and experimental 550 kV cables with 1.025 inch and 1.340 inch insulation thicknesses, respectively.

Soft-spots develop due to irreversible migration of the paper tapes where the cable flexes due to the thermal expansion and contraction of the conductor during load cycling.

The commercial (345 kV) problems to date have been almost exclusively confined to early design state-of-the-art cables and in joint casings where the cables are intentionally offset to permit splicing.

Soft-spots at 345 kV have also occurred where overfilled casings permit large lateral movement to accommodate both cable migration and expansion.

As a countermeasure, additional special supports (spiders) are now installed on the cables within the joint casing, effectively rigiding the splice so that the thermal expansion must be absorbed within the line pipe. The objectives of a current PTI study (EPRI/ESEERCO Contract RP7873) are to examine the cables' bending behavior within the line pipe, and, through experimental and theoretical analysis, evaluate the mechanism(s) by which soft-spots develop.

The accelerated mechanical tests are being done in a 3-conductor, 20 ft. sample length TMB (thermo-mechanical bending) machine where the thermal expansion/contraction is simulated by a hydraulic cylinder pushing/pulling against the 3 cables at one end. Figure 1 shows a 345 kV cable installed in a 12-inch line pipe (oversized pipe).

FIGURE 1
20 FT. SAMPLE LENGTH 3-CONDUCTOR TMB TEST STRUCTURE

The testing to date has utilized cable sizes ranging from 2250 kcmil copper conductor through 3750 kcmil aluminum conductor; insulation thicknesses from 0.620 inch through 1.250 inch; skidway materials of zinc, stainless steel and polyethylene; and pipe diameters of 8, 10, and 12 inches. Through this testing, it has been observed that the soft-spot does not always develop at the minimum radius bend. Rather, they may develop to an area where the cable is being bent and bound during the compressive part of the cycle corresponding to thermal expansion.

The cables bend within the line pipe in a sinuosidal and helical configuration, but measurements indicate that no rotation of the individual cables occurs during this bending.

A single-conductor test apparatus was designed and built in which the cable is tested in one plane rather than the helical configuration in the 3-conductor machine. Thus far the result of testing in one plane supports the theory that both friction against the pipe and cable bending are required to develop a soft spot. The single-conductor testing is a very reproducible test method with excellent correlation to actual field behavior of the cable when only looking at one bend.

The testing to date has been on unused cables manufactured within the last few years, except for two tests on cables manufactured and installed in 1973 and removed from service in 1981.

Cables to be manufactured with pronounced design variations are on order from the cable manufacturers and, from testing these constructions, the effects of changes in the cable constructional variables can be investigated.

Present tests on modern constructions indicate that the force against the pipe wall and the bending radius will be relieved by another bend before the critical compression and bending radius are reached. The Pirelli Cable Corporation, a subcontractor for this project, will be testing a strain of these cable constructions in a 65 ft. long TMB machine. The first tests confirm that the cables will continue to form new bends until the pipe is filled with bent cable. Both the Pirelli machine and the PTI 3-conductor 20 ft. long sample length simulate the Waltz Mill test site observations very well. Waltz Mill is the longer term, full scale EPRI test facility in Pennsylvania. It is believed the bending patterns, especially at small increments of pushing are very similar to those found in field installations.

The specification and testing of TMB-resistant cables based on study results is included in the scope of the PTI project.

Long Term Simulation (continued from page 2)

Each of these has a time frame associated with it, and may impact the system beneficially or adversely during the time frame. Each can be represented in the load flow or stability analysis as appropriate for the point in time being examined. Examination of these effects as well as possible equipment failures and operator errors will provide valuable insight into potential system weaknesses that can lead to cascading.

Dynamic instability can contribute to a cascading outage in a system even though the system is dynamically stable immediately following the initial disturbance. Degradation of normal system damping characteristics may occur as stress increases in the minutes following a disturbance. Additionally, minor events that follow a significant initiating event may not represent a transient stability threat, but may lead to a condition wherein dynamic instability can occur.

In addition to the load flow and stability analysis discussed above, there are other programs that have proven very helpful in the analysis of long-term effects, including overload cascading and islanding. The PTI PCAP program has been used to define potential overload cascading sequences and probable resulting islands. TPLAN provides convenient analysis of voltage and overload problems in systems under stress.

Cascading outages tend to have two components. Predictable system responses that negatively affect the system, worsening the stress it is under, and unpredictable operator actions and latent weaknesses or failures in equipment. The predictable responses can be readily analyzed and corrected or mitigated by application of existing programs. The unpredictable responses are not going to be solved by any program no matter how detailed the simulation. A failure such as a stuck valve or open relay coil in a power plant will not be revealed by a simulation. The engineer must envision an array of such problems and test the system response to the consequences of such failures (e.g. trip of a plant called on to undergo a rapid power change).

A skilled engineer with modern flexible load flow, stability and related programs can analyze both the expected responses and assumed latent failures, gaining valuable insight into system weakness and the effects of various system design alternatives on susceptibility to cascading outages.
DENISON NAMED TO NEW PRINCIPAL ENGINEER POST

Effective June 1 of this year, Oscar J. Denison, Jr. was appointed a Principal Engineer of PTI, responsible for marketing and coordination of business development. As PTI has grown, the engineering services area has become more diverse and the software area has become a major "product" business. Denison's strong technical background and perspective into the technological trends within the power industry equips him well for supporting PTI's engineering staff in their sales efforts and for providing corporate guidance in market development. An internationally known expert in energy control systems, he has been responsible for PTI's power systems operations area. Denison joined PTI in 1975, having formerly served as a senior staff engineer of TRW Controls Corporation in Houston.

PSS/E USERS MEET IN SEATTLE

The fifth PSS/E Users’ Group Meeting was held on May 19 in Seattle, Washington. Three PTI engineers hosted forty-five engineers representing twenty-one of the fifty-five utility organizations which have adopted PSS/E.

The purpose of these annual gatherings is to discuss technical points of common interest, to keep users informed of our development plans, and to provide a user feedback mechanism which has become a significant input in guiding the evolution of PSS/E.

State Estimation (continued from page 1)

A second phase of implementation is testing the performance of the state estimator using actual, rather than computer-simulated, measurements. During this phase, gross meter errors, errors in assumed values of line impedances, and other such data errors are uncovered. It has been PTI’s experience that, prior to state estimator implementation, such errors in the network data base have gone undetected by the utility for years; the bad data detection capability of the state estimator was required to uncover them. Further "tuning" of the state estimator occurs during this phase. Assumed values of transducer accuracy are compared to actual measurement data and adjusted accordingly. After this "shakedown" period, the state estimator is ready to be placed into real-time operation.

Concern has been expressed about the acceptance of the state estimation function by utility operating personnel. Careful attention must be given to computer program design to ensure that its output format and interactive capabilities are of a form that is most useful to the people who will be using it on a daily basis. It has been our experience that, when such consideration is given, the state estimation function is enthusiastically accepted by the system operators.

State estimation for electric power systems was first proposed about fifteen years ago. Its widespread implementation, however, has only occurred within the recent past. Fifteen years ago, little was known about metering requirements or about the numerical properties of state estimation algorithms for large networks. These areas are better understood today and, as a result, implementation of the state estimation function in large electric power networks is now practical. It appears that state estimation will become one of the standard on-line functions performed in modern control centers in the not-too-distant future.

ADVANCED ENGINEERING COURSES — FALL 1982 SCHEDULE

Each course listed below can be presented in other locations, provided sufficient interest is shown. The tuition shown for each course is per participant. Please direct inquiries to Margaret Stambach, Senior Engineer.

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<td>Schenectady</td>
<td>$900</td>
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<td>Power System Dynamics</td>
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<td>Transmission Reliability Assessment</td>
<td>Oct. 12-14</td>
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