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LOAD REPRESENTATION FOR DYNAMIC PERFORMANCE ANALYSIS

IEEE Task Force on
Load Representation for Dynamic Performance

Abstract - This paper summarizes the state of the art of representation of power system loads for dynamic performance analysis purposes. It includes definition of terminology, discussion of the importance of load modeling, important considerations for different types of loads and different types of analyses. Typical load model data and methods for acquiring data are reviewed. A list of recent references is included.

Key Words - Load Modeling, Power System Modeling, Power System Dynamic Performance.

1. INTRODUCTION

The purpose of this paper is to review the current state of the art of power system load representation for dynamic performance analysis. The power system engineer bases decisions concerning system reinforcements and/or system performance in large part on the results of power flow and stability simulation studies. Representation inadequacies that cause under- or over-building of the system or degradation of reliability could prove to be costly. In performing power system analysis, models must be developed for all pertinent system components, including generating stations, transmission and distribution equipment, and load devices. Much attention has been given to models for generation and transmission/distribution equipment. The representation of the loads has received less attention and continues to be an area of greater uncertainty. Many studies have shown that load representation can have a significant impact on analysis results. Therefore, efforts directed at improving load modeling are of major importance.

One objective of this paper is to summarize basic load modeling concepts and provide guidelines for different types of dynamic performance analysis. The accurate modeling of loads continues to be a difficult task due to several factors, including:

a. Large number of diverse load components,

b. Ownership and location of load devices in customer facilities not directly accessible to the electric utility,

c. Changing load composition with time of day and week, seasons, weather, and through time,

d. Lack of precise information on the composition of the load.

e. Uncertainties regarding the characteristics of many load components, particularly for large voltage or frequency variations.

Utilities often collect information on load composition for load forecasting purposes. However, this information is sometimes not readily accessible or in usable form for system analysis purposes. Recent advances in techniques for measuring load characteristics and for determining them from composition data can contribute to more accurate load representation. A second objective of this paper is to review these techniques, identify data sources and encourage more extensive load data acquisition.

This paper is divided into ten sections. Basic load modeling concepts and definitions are given in Section 2. The need for improved load representation is discussed in Section 3. Section 4 describes current industry practice, based on a survey conducted by the task force. Section 5 is a discussion of issues to be considered in selecting load models. Section 6 presents guidelines for applying load models to specific types of studies. The data for load models is discussed in Section 7, including both measurement-based and component-based methods of obtaining data. Typical data is also given. Techniques for validating load representation are discussed in Section 8. Conclusions regarding the state-of-the-art and further R&D needs are presented in Section 9. A list of recent references is given in Section 10.

2. BASIC LOAD MODELING CONCEPTS

This section provides basic definitions and concepts related to load modeling.

LOAD - The term "load" can have several meanings in power system engineering, including:

a. A device, connected to a power system, that consumes power,

b. The total power (active and/or reactive) consumed by all devices connected to a power system,

c. A portion of the system that is not explicitly represented in a system model, but rather is treated as if it were a single power-consuming device connected to a bus in the system model.

d. The power output of a generator or generating plant.

Where the meaning is not clear from the context, the terms, "load device", "system load", "bus load", and "generator or plant load", respectively, may be used to clarify the intent.

Definition "c" is the one that is of main concern in the present paper. As illustrated in Figure 1, "load" in this context includes, not only the connected load devices, but some or all of the following:

- Substation step-down transformers
- Subtransmission feeders
- Primary distribution feeders
- Distribution transformers
- Secondary distribution feeders
- Shunt capacitors
- Voltage regulators
- Customer wiring, transformers, and capacitors

Accurate load representation therefore requires accounting for the effects of these elements. Exactly what is included in the "load" depends on what is and is not represented in the system model. Studies of bulk power transmission systems often omit much of the subtransmission as well as the distribution system.

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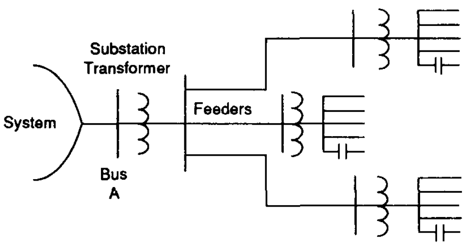


Figure 1 "Bus Load", including feeders, transformers, and shunt capacitors, as well as load devices.

In describing the composition of the load, the following terms, illustrated in Figure 2, are recommended:

LOAD COMPONENT - A load component is the aggregate equivalent of all devices of a specific or similar type, e.g., water heater, room air conditioner, fluorescent lighting.

LOAD CLASS - A load class is a category of load, such as, residential, commercial, or industrial. For load modeling purposes, it is useful to group loads into several classes, where each class has similar load composition and load characteristics.

LOAD COMPOSITION - The fractional composition of the load by load components. This term may be applied to the bus load or to a specific load class.

LOAD CLASS MIX - The fractional composition of the bus load by load classes.

LOAD CHARACTERISTIC - A set of parameters, such as power factor, variation of P with V, etc., that characterize the behavior of a specified load. This term may be applied to a specific load device, a load component, a load class, or the total bus load.

The following terminology is commonly used in describing different types of load models:

LOAD MODEL - A load model is a mathematical representation of the relationship between a bus voltage (magnitude and frequency) and the power (active and reactive) or current flowing into the bus load. The term "load model" may refer to the equations themselves or the equations plus specific values for the parameters (e.g., coefficients, exponents) of the equations. Depending on the computational implementation of these equations in a specific program, the load power or current may not be calculated explicitly, but it is useful to think of the model in these terms.

STATIC LOAD MODEL - A model that expresses the active and reactive powers at any instant of time as functions of the bus voltage magnitude and frequency at the same instant. Static load models are used both for essentially static load components, e.g., resistive and lighting load, and as an approximation for dynamic load components, e.g., motor-driven loads.

DYNAMIC LOAD MODEL - A model that expresses the active and reactive powers at any instant of time as functions of the voltage magnitude and frequency at past instants of time and, usually, including the present instant. Difference or differential equations can be used to represent such models.

CONSTANT IMPEDANCE LOAD MODEL - A static load model where the power varies directly with the square of the voltage magnitude. It may also be called a constant admittance load model.

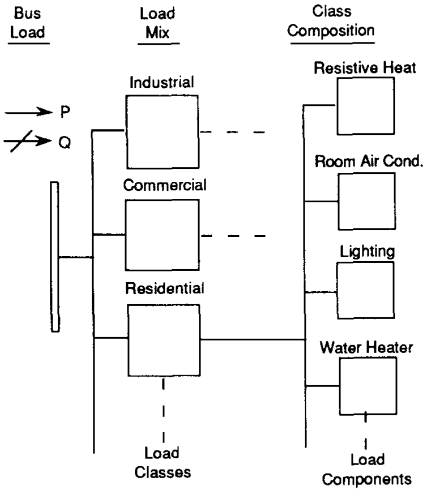
CONSTANT CURRENT LOAD MODEL - A static load model where the power varies directly with the voltage magnitude.

CONSTANT POWER LOAD MODEL - A static load model where the power does not vary with changes in voltage magnitude. It may also be called constant MVA load model. Because constant MVA devices, such as motors and electronic devices, do not maintain this characteristic below some voltage (typically 80 to 90%), many load models provide for changing constant MVA (and other static models) to constant impedance or tripping the load below a specified voltage.

POLYNOMIAL LOAD MODEL - A static load model that represents the power relationship to voltage magnitude as a polynomial equation, usually in the following form:

$$P = P_0\left[a_1\left(V/V_0\right)^2 + a_2\left(V/V_0\right) + a_3\right]$$

$$Q = Q_0\left[a_4\left(V/V_0\right)^2 + a_5\left(V/V_0\right) + a_6\right]$$



Component Characteristics					
p.f.	$\frac{dP}{dV}$	$\frac{dQ}{dV}$	$\frac{dP}{df}$	$\frac{dQ}{df}$	Motor Parameters
1.	2.	0.	0.	0.	-
.82	.5	2.5	0.6	-2.8	etc.
1.	1.54	0.	0.	0.	-
1.	2.	0.	0.	0.	-

Figure 2. Terminology for Component-Based Load Modeling.

The parameters of this model are the coefficients (a_1 to a_6) and the power factor of the load. This model is sometimes referred to as the "ZIP" model, since it consists of the sum of constant impedance (Z), constant current (I), and constant power (P) terms. If this, or other, models are used for representing a specific load device, V_o should be the rated voltage of the device, and P_o and Q_o should be the power consumed at rated voltage. However, when using these models for representing a bus load, V_o, P_o, and Q_o are normally taken as the values at the initial system operating condition for the study. Polonomials of voltage deviation from rated (ΔV) are also sometimes used [24].

EXPONENTIAL LOAD MODEL - A static load model that represents the power relationship to voltage as an exponential equation, usually in the following form:

$$P = P_o \left({}^{V}\!/_{V_o} \right)^{np}$$

$$Q = Q_o \left({}^{V}\!/_{V_o} \right)^{nq}$$

Two or more terms with different exponents are sometimes included in each equation. The parameters of this model are the exponents, np and nq, and the power factor of the load. Note that by setting these exponents to 0, 1, or 2, the load can be represented by constant power, constant current, or constant impedance models, respectively. Other exponents can be used to represent the aggregate effect of different types of load components. Exponents greater than 2 or less than 0 may be appropriate for some types of loads.

FREQUENCY-DEPENDENT LOAD MODEL - A static load model that includes frequency dependence. This is usually represented by multiplying either a polynomial or exponential load model by a factor of the following form:

$$\left[1. + a_f \left(f - f_o\right)\right]$$

where f is the frequency of the bus voltage, f_o is the rated frequency, and a_f is the frequency sensitivity parameter of the model.

Bus Frequency - The frequency of the bus voltage is not an inherent variable in fundamental-frequency network analysis and is not used in many dynamic performance analysis programs. However, it can be computed by taking the numerical derivative of the bus voltage angle. This frequency is required, not only in the static frequency-dependent load model, but also in some other load models, such as a dynamic induction motor model. The bus frequency is sometimes approximated by using an average system frequency, computed from a weighted average of synchronous machine speeds. This approximation is wrong because it will not produce the correct impact on damping of oscillations.

EPRI LOADSYN STATIC LOAD MODEL - The static model used in the EPRI LOADSYN program [12]:

$$P = P_o \left\{ P_{a1} \left({}^{V}\!/_{V_0} \right)^{KPV1} \left[1 + KPF1(f - f_o)\right] + (1 - P_{a1}) \left({}^{V}\!/_{V_o} \right)^{KPV2} \right\}$$

$$\begin{aligned} Q = P_o \Big\{ & Q_{a1} \left({}^{V}\!/_{V_0} \right)^{KQV1} \left[1 + KQF1(f - f_o)\right] \\ & + \left({}^{Q_o}\!/_{P_o} - Q_{a1} \right) \left({}^{V}\!/_{V_o} \right)^{KQV2} \left[1 + KQF2(f - f_o)\right] \Big\} \end{aligned}$$

The active power is represented by two aggregate components, one frequency-dependent and the other not. The first term of the reactive power equation represents the reactive consumption of the all of the load components. The second term approximates the effect of the net reactive consumption of feeders and transformers minus shunt capacitance, included in the "bus load", to give the specified initial reactive flow (Q_o) at the bus.

EPRI ETMSP STATIC LOAD MODEL - The general model used in the EPRI Extended Transient Mid-term Stability Program [23]:

$$P = P(CI) + P(CMVA) + P(CZ) + P(V,f)$$

$$Q = Q(CI) + Q(CMVA) + Q(CZ) + Q(V,f)$$

where:

$$P(CI) = P_o \; (ICONCP/100) \; (V/V_o)$$

$$Q(CI) = Q_o \; (ICONCQ/100) \; (V/V_o)$$

$$P(CMVA) = P_o \; (ICONPP/100)$$

$$Q(CMVA) = Q_o \; (ICONPQ/100)$$

$$P(CZ) = P_o \; (ICONZP/100) \; (V/V_o)^2$$

$$Q(CZ) = Q_o \; (ICONZQ/100) \; (V/V_o)^2$$

$$\begin{aligned} P(V,F) = P_o \Big[& \left(K_{p1}/100\right) \; (V/V_o)^{a1} \; \left(1 + Kpf1(f - f_o)\right) \\ & + \left(K_{p2}/100\right) \; (V/V_o)^{a2} \; \left(1 + Kpf2(f - f_o)\right) \Big] \end{aligned}$$

$$\begin{aligned} Q(V,F) = Q_o \Big[& \left(K_{q1}/100\right) \; (V/V_o)^{b1} \; \left(1 + Kqf1(f - f_o)\right) \\ & + \left(K_{q2}/100\right) \; (V/V_o)^{b2} \; \left(1 + Kqf2(f - f_o)\right) \Big] \end{aligned}$$

$$ICONZP = 100 - ICONCP + ICONPP + KP1 + KP2$$

$$ICONZQ = 100 - ICONCQ + ICONPQ + KQ1 + KQ2$$

INDUCTION MOTOR - For modeling of induction motors, most stability programs include a dynamic model based on the equivalent circuit shown in Figure 3. Other features available in some programs are additional rotor circuits, saturation, low voltage tripping, and variable rotor resistance.

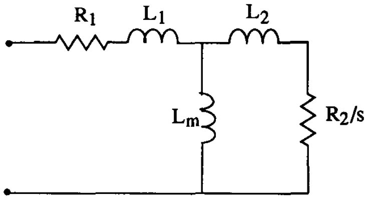


Figure 3. Induction motor equivalent circuit, where "s" is the motor slip, R_2 and L_2 are rotor values, R_1 and L_1 are armature values, and L_m is the magnetizing inductance.

It is important to note that the "slip" used in this model is the frequency of the bus voltage minus the motor speed. Some programs incorrectly use either average system frequency or 1.0 in place of the bus frequency. As with the frequency-dependent load, such approximations will incorrectly represent damping effects.

Several levels of detail, based on this equivalent circuit, may be available, including:

1. A dynamic model including the mechanical dynamics but not the flux dynamics,
2. Addition of the rotor flux dynamics,
3. Addition of the stator flux dynamics.

Stator flux dynamics are normally neglected in stability analysis and the rotor flux dynamics may sometimes be neglected, particularly for long-term dynamic analysis. Low voltage tripping is an important feature for voltage stability analysis and other studies involving sustained low voltage.

CLOAD MODEL - A load model used in the PTI PSS/E stability program including dynamic models of aggregations of large and small motors, non-linear model of discharge lighting, transformer saturation effects, constant MVA, shunt capacitors, and other static load characteristics and a series impedance and tap ratio to represent the effect of intervening subtransmission and distribution elements.

LOAD POWER ORDER - The value of the bus load (P and/or Q) at rated voltage and frequency. In most studies, this value is held invariant throughout a simulation, so that the only variations in load P and Q are due to changes in system voltage and frequency. However, load power order can be varied in some studies, e.g., to analyze voltage stability during a load ramp or to study the effect of impact loads such as arc furnaces. This term has been coined recently to clarify the distinction between this quantity and the power demand, which is the power consumed at the actual voltage and frequency.

3. NEED FOR IMPROVED LOAD REPRESENTATION

Electric utility analysts and their management require evidence of the benefits of improved load representation in order to justify the effort and expense of collecting and processing load data and, perhaps, modifying computer program load models. The benefits of improved load representation fall into the following categories:

A. If present load representation produces overly-pessimistic results:
   1. In planning studies, the benefits of improved modeling will be in deferring or avoiding the expense of system modifications and equipment additions,
   2. In operating studies, the benefits will be in increasing power transfer limits, with resulting economic benefits.

B. If present load representation produces overly-optimistic results:
   1. In planning studies, the benefit of improved modeling will be in avoiding system inadequacies that may result in costly operating limitations,
   2. In operating studies, the benefit may be in preventing system emergencies resulting from overly-optimistic operating limits.

In addition, failure to represent loads in sufficient detail may produce results that miss significant phenomena.

It is difficult to quantify the benefits of improved load representation. Several studies, reported in the literature, have demonstrated the impact that different load models can have on the results of different types of studies. In some cases, the impact can be significant. A recent voltage stability study for the Pacific Northwest System showed that when the heating load of the residential part of the winter peak load was represented accurately (close to constant impedance for first-swing stability studies), a considerably higher transfer limit was achieved. This may result in a major saving in capital expenditure. On the other hand, an optimistic load model could result in pushing systems beyond their actual limits and making them vulnerable to major collapses. For example, the Tokyo system collapse of 1987 was partly due to underestimating the characteristics of the reactive power consumption of air-conditioning loads.

A common philosophy, in the absence of accurate data on load characteristics, is to assume what is believed to be a pessimistic representation, in order to provide some safety margin in the system designs or operating limits. This has been shown to be a dangerous approach because it is not always possible to select representations that will be pessimistic for all parts of the system or all test conditions. Some of the reasons for this are as follows:

First-Swing Transient Stability Studies

System voltages are normally depressed during the first angular swing following a fault. The power consumed by the loads during this period will affect the generation-load power imbalance and thereby affect the magnitude of the angular excursion and the first-swing stability of the system.

Consider a case where the loads have a constant current characteristic (power consumption varies directly with the magnitude of the voltage) [12]. If a constant impedance load model were used, the power consumption would vary with the square of the voltage and, therefore, would be lower than the actual load during the depressed voltage period. For loads near accelerating machines this will give pessimistic results, since the generation-load imbalance will be increased. However, for loads remote from the accelerating machines (near decelerating machines), there will be an optimistic impact on the results. On the other hand, a constant MVA load model would have the opposite impact on the results since it would hold the load power at a higher value during the depressed voltage. It is therefore difficult to select a model that is guaranteed to be conservative for all parts of the system and for various disturbances.

Also, static load models have proved to be inadequate in cases involving large deviations of voltage and/or frequency, especially in islanding situations [15]. For example, if a disturbance results in islanding some part of a system with a deficiency in generation accompanied by considerable drop in voltage, a constant impedance load model may indicate a frequency rise rather than drop. Moreover, while constant MVA is considered by many as a conservative representation for induction motor loads this may be true only for the active part of the load. The reactive power part, however, is in fact expected to increase as the voltage decreases beyond a certain value. In these cases, there is no substitute for realistic dynamic load models.

Small-Signal Stability Damping Studies

Inter-area modes of oscillation, involving a number of generators widely distributed over the power system, often result in significant variations in voltage and local frequency. In such cases, the load voltage and frequency characteristics may have a significant effect on the damping of the oscillations. A recent study [16] for the western North America power system showed that using a constant impedance load representation in small signal analysis tended to overestimate the damping by about 25% as compared with a more accurate load representation.

Voltage Stability Analysis

Voltage stability analysis is a class of studies that does not lend itself to simple static load modeling. Reference [10] shows the extent of load model details that the Swedish State Power Board had to use to duplicate the field records of the 1983 blackout. Initial efforts using simple static load models failed to explain the voltage collapse scenario. It was then recognized that the load characteristics at low voltages (below 0.8 pu) will not follow the characteristics that are traditionally used in stability studies. Detailed characteristics of induction motors, lighting, refrigerators, and air conditioners are explained in the reference.

Voltage stability studies done at Ontario Hydro for the Ottawa Area reemphasized the need for accurate dynamic load modeling. In a study of the impact of the loss of one of the transmission lines feeding the area, a substantial difference was found between the results obtained with static and dynamic models. The former led to entirely the wrong conclusion [15].

While it is often assumed that the nearly constant MVA characteristics of induction motors will produce the most severe results, B.C. Hydro's experience in the 1979 voltage collapse incident of the northern part of the British Columbia system showed the fallacy in generalizing this conclusion. The constant impedance characteristics of arc furnaces near the sending end of a radial system resulted in increasing transfer to the receiving end due to the load reduction with voltage near the sending end [22].

Summary

The foregoing discussion indicates that there is no general rule as to which load model is reasonable to use. It is this task force's opinion that there is no substitute for spending the effort to identify the actual load characteristics of a given system and to use models appropriate to the type of study being performed. A considerable improvement in modeling fidelity can be achieved by fully utilizing existing models including dynamic models. However, further development, as described in Section 9, is also needed.

4. CURRENT INDUSTRY PRACTICE

A survey regarding current industry practices and research was taken by the task force. The survey was sent late in 1988 to approximately 85 industry representatives, mostly in North America, with a 40% response rate. A majority of those who responded were not using special load modeling software. Of those who were, the majority were using the EPRI LOADSYN package.

For pre- and post-contingency power flow analysis, constant MVA load models were the overwhelming choice. However, several utilities did report using voltage-dependent load models for this type of analysis.

For first-swing and small-signal stability analysis, constant current for active power load and constant admittance for reactive load was the dominant choice, though it was by no means overwhelming. Other load models reported in use included constant admittance for both active and reactive load, static polynomial models, and combinations of the above. At least two utilities reported the use of dynamic induction motor models for certain types of stability analysis.

The survey results indicated that approximately 50% of those who responded were dissatisfied with their present load models and were pursuing work to improve them. This work included gathering more detailed end-use data, installing digital and/or transient recorders at selected locations within their systems, and conducting field tests to develop new models or validate existing representations.

Several of the industry representatives who responded to the survey raised concerns with regard to data-gathering difficulties. It was perceived to require a great deal of data-gathering effort to utilize the more complex load models. It was suggested that the LOADSYN program provide generic data for a wider range of industries similar to that already supplied for steel mills and aluminum plants. In addition, it was suggested that more research work be done in the area of data acquisition.

5. LOAD MODELING CONSIDERATIONS

A number of modeling considerations have been discussed in Section 3 to indicate the importance of good load modeling. This section summarizes these and other important considerations for the following types of system dynamic performance studies:

- first-swing,
- small-signal
    - damping,
    - synchronizing power,
- load-generation imbalance,
- induction motor stability,
- cold-load pickup,
- voltage stability, and
- dynamic overvoltages.

Whether or not a particular load component should be modeled in detail in a study depends on how much the component response affects the voltage and frequency excursions typical of that type of study. Each of the above studies poses unique load modeling requirements as outlined in the brief introductory paragraphs that follow.

First-Swing -- First-swing problems exhibit large and rapid voltage excursions during the initiating fault and slower voltage excursions during the first power-angle swing, which lasts one second or less. Load response to these voltages is important, as discussed in Section 3. There is also a brief frequency excursion during the power-angle swing, so frequency characteristics of loads close to accelerating or decelerating generators can also be important.

Small-Signal Stability Damping -- In studies of the damping of power-angle oscillations, typically in the range 0.1 to 1.2 Hz, load response to sinusoidal variations in voltage and frequency is important. Frequency variations are greatest near machines with the greatest participation in the particular mode of oscillation. Voltage variations tend to be greatest at intermediate points between opposing machines or groups of machines.

Synchronizing Power Margin -- Studies of synchronizing power margins may require evaluation of periods from one or two minutes to 20 minutes or more after a disturbance, thus making long-term load characteristics important. Long-term load voltage characteristics and tap-changing transformers (LTCs) near the electrical center of a system will be important when angles across a system approach 90°.

Generation-Load Unbalance -- In studies of generation-load unbalance, response of load components to frequency decay rates in the range 0.1 to about 4 Hz per second is important. For low frequency decay rates, loads follow their long-term voltage and frequency characteristics, while inertia and, sometimes, electrical time constants of motors can come into play at higher frequency decay rates.

Induction Motor Stability -- In studies of induction motor stability, the important question is whether motors will reaccelerate or stall following fault clearing. Motor and shaft load inertia, contactor hold-in characteristics, and motor electrical parameters such as the rotor circuit time constant can be as important as the stiffness of the system.

Cold Load Pickup -- In cold load pickup studies, almost all customer load device characteristics are important. For instance, thermostats and people may add load devices to the system while the feeder is open, while protective devices may disconnect some motors. Motor starting current and inertia affect the current in the feeder in the first seconds after it is reclosed. Distribution substation LTCs are very important, and if not modeled explicitly, must be made a part of the load model.

Voltage Stability -- Voltage stability is usually a longer-term problem much like that of maintaining synchronizing power margins to avoid instability, and the load modeling requirements are similar. Characteristics of loads under abnormally low voltage conditions and the action of LTCs and other voltage control devices must be accurately modeled.

Dynamic Overvoltages -- Dynamic overvoltages are usually associated with sudden loss of line or network loading as can occur upon bypassing or blocking of HVDC converters, load rejection on radial generation, and instability and breakup in higher voltage networks and networks in which shunt capacitors or cables are heavily used. A dynamic overvoltage study may address the design of an static var system (SVC) to limit overvoltages or the risk of generator self-excitation. Though not much load may be in the problem area or left on the network when the overvoltages occur, even a small quantity of load can have a significant effect. Hence load response to voltage, and in particular, saturation characteristics of load devices, will be important. Since harmonics will affect the overvoltage, fundamental frequency analysis is not always adequate for such studies.

Load Characterization

Loads can be categorized as follows:

- loads that exhibit 'fast dynamic' electrical and mechanical characteristics - the primary examples are the mechanical and electrical time constants of induction motors. Adjustable speed drives are another example, though they respond so quickly to voltage and frequency that they exhibit their longer-term characteristic throughout most time simulations.
- loads whose response to voltage excursions exhibit significant discontinuities; examples include:
    - discharge lighting (constant current active part, voltage to 4th power for reactive part, extinguish at about 80% of rated voltage),
    - adjustable speed drives that shut down on low voltage (as high as 90% of rated voltage),
    - motor contactors that drop open during faults and voltage swings, removing motor load from the system, and
    - motor overload protection that removes stalled motors from the system after about 10 seconds

- loads whose response to voltage excursions does not exhibit significant discontinuities or time lags; examples include:
  - very small motors,
  - incandescent lighting,
  - uncontrolled resistive loads
- loads with 'slow dynamic' characteristics such as:
  - loads controlled by thermostats and manually-controlled loads that are initially constant resistance, but change to constant power over a 10 to 20 minute period after a change in voltage.

Specific load device characteristics include:

Motors -- A motor's inertia and rotor flux time constant are key determinants of the motor's active and reactive power response to the voltage and frequency swings that characteristically follow faults. Reaccelerating motors near accelerated generators tend to slow generators and improve stability. Reaccelerating motors in weak areas pull voltage down, reduce synchronizing power and thus degrade stability. Motor starter contactors may drop open at 65-75% in the case of 2300 and 4000 V motors and 55-65% in the case of motors at 460 V and below. Motors may drop during the fault, or during the voltage excursion that follows the fault. Near sending-end generators, this will degrade stability as the lost load power adds to transfers. Near the receiving end or in weak areas, the loss of motor load may improve stability. Motor active and reactive power lead voltage and frequency during sinusoidal voltage and frequency variations, usually degrading damping. Motors consume about 70% of the electrical energy in the U.S., and are thus clearly an important load element.

Air Conditioners -- As load devices, air conditioners fall into the motor category, but many air conditioners are not served by contactors and thus do not drop from the system during faults and voltage excursions. Because of low inertia, air conditioners slow considerably during faults, and thus impose large, low power factor 'starting currents' on the network after the fault is cleared. If the network is not strong enough to reaccelerate all of the air conditioners simultaneously, voltage will be depressed and the air conditioner speeds will continue to decay. The constant-torque mechanical load imposed by the loaded compressor and the low starting torque design of the motor (the motor is chosen only to start an unloaded compressor) contribute to the tendency to stall. Because the voltage is low, overload protection is slow to operate; taking typically 10 to 12 seconds to remove the air conditioners from the system. Voltage begins recovering as the air conditioners are removed, but all air conditioners must be tripped by overload protection even if voltage recovers fully because at low speed motor torque will be below that of the loaded compressor. Air conditioning can be as much as 50% of the summer load in some areas.

Discharge Lighting -- Discharge lighting includes mercury vapor, sodium vapor, fluorescent, and similar types widely used in industry and for parking lots and street lighting. This type of load may represent up to 20% of system load in commercial areas. This load extinguishes at about 80% voltage, and thus may drop to zero during faults and when voltages swing down during a power-angle swing. A momentary drop in load near the electrical center of a system (where the voltage excursion is the largest, see Figure 4) will usually improve the first-swing. On the other hand, lighting near 'sending end' generators that extinguishes and takes one to two seconds to restart after the fault, can increase generator acceleration and thus degrade stability.

At voltages above the extinguishing point, conventional discharge lighting is typically constant current active part and voltage to the 4th power reactive part. This reactive characteristic can help stabilize voltage even where voltage does not reach the extinguish point. The newer electronic ballasts, high efficiency lamps, and light-controlled dimming fixtures are closer to a constant MVA load, but their extinguish points need to be explored.

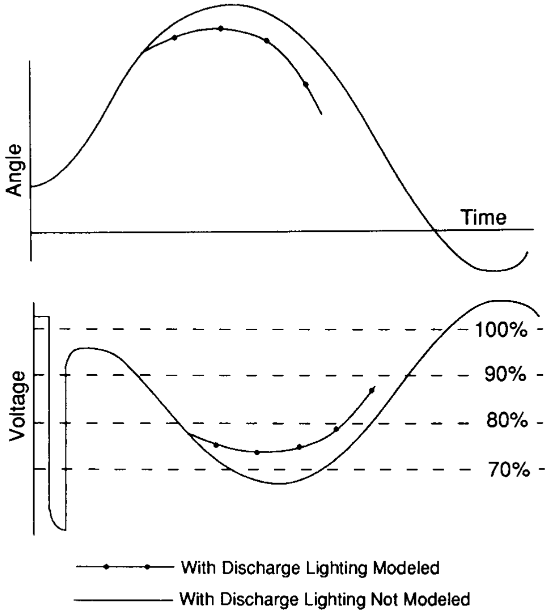


Figure 4. When voltages swing below 80% following fault clearing, discharge lighting will extinguish, reduce system load, and stabilize voltage between 70 and 80%. This will improve stability as shown in this figure.

Incandescent Lighting -- Incandescent lamps are often assumed to have a constant resistance characteristic. However, due to the large temperature swing that occurs in the filament when voltage changes, the filament resistance changes with voltage. The result is active power that varies with about the 1.55 power of voltage; about halfway between constant current and constant resistance.

There is a thermal time constant associated with incandescent lamps, but it is short compared with other time constants of concern in stability analysis. Only in lamps above about 200 W is the thermal time constant large enough to be of concern.

Thermostat-controlled Loads -- Many loads, such as space heaters, molding and packaging machines, soldering machines, water heaters and the like, are very close to a constant resistance characteristic -- in the short-term. Such loads operate in a temperature range where the effect of changes in power input do not change temperature enough to measurably affect resistance. However, beginning just seconds after a drop in voltage, the reduction in heat output from such devices will be sensed by thermostats and the 'on' part of the thermostat cycle will be extended. Thermostats that are in the 'off' period of their cycle when the voltage change occurs will not respond to the voltage drop until they enter the 'on' portion of their cycle.

Figure 5 shows the temperature profile of a thermostat-controlled load with 100% and 90% voltage. As would be expected, temperature rises more slowly than normal during the 'on' portion of the cycle when voltage is low, but temperature drops at the same rate during the off portion of the cycle. However, the average temperature, and thus the average power input, are the same in both cases. Because of the longer 'on' period, more thermostats are in the 'on' mode at any given instant when voltage is low, and the total load is thus the same as it is at normal voltage. The result is that thermostat-controlled loads are, effectively, constant power loads on a long-term basis. Since cycle periods vary (5 to 30 minutes), the load will completely restore only after the 'off' period of the longest thermostat period.

There are possible exceptions. Where voltage is so low that some thermostats can not be 'satisfied,' the load will not be fully restored. Similarly, on a very cold day, thermostats on electric space heating may already be 'on' at or close to 100% of the time, so that full restoration does not occur following a drop in voltage.

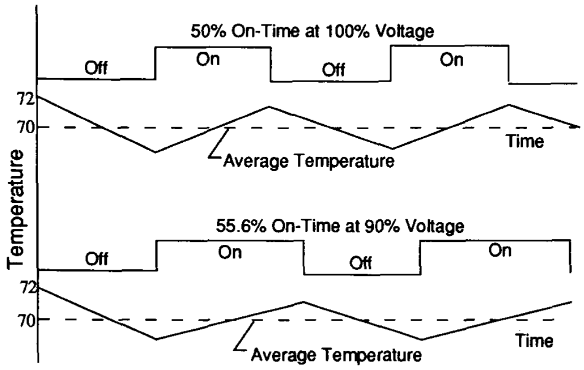


Figure 5. When voltage is low, thermostats on "resistance type loads" remain closed longer, effectively restoring the load to a constant power characteristic in the steady-state.

There are many industrial, commercial, and residential load devices that have this characteristic. This component may make up 20 to 40% of the system load.

In first-swing studies and damping studies of less than about 5 minutes, thermostat-controlled loads should be given a constant resistance characteristic. For long-term studies of several minutes or more duration, a dynamic characteristic, which changes from constant resistance to constant power with a suitable time constant, should be used.

Manually Controlled Loads -- Manually controlled loads are quite similar to thermostat-controlled loads. For instance, a pot of water will be left on an electric range until boiling is clearly visible. If voltage is low, the water will remain on the electric range for a longer than normal period. Many people doing the same thing results in more pots of water on ranges at any given instant when voltage is low. This component of load makes the transition from constant resistance to constant power in several minutes.

Electronic Devices (Regulated Power Supplies) -- Many electronic devices (e.g., computers, microwave ovens, TVs) include switch-mode and other regulated power supplies. These power supplies will provide a constant dc output for input voltage down to about 90% of normal. Hence they are effectively constant power down to this voltage. Below this voltage some of these loads will cease to function, though some will continue to draw power. The power input thus may drop when voltage falls below about 90% of rated voltage.

Adjustable Speed Drives -- Adjustable speed drives are like computers and electronic equipment, except that shutdown will typically occur when voltage drops below the lowest tolerance, about 90% of normal. Response to voltage is fast relative to rotor angle oscillations, so such loads are effectively constant power even in first-swing and small-signal stability studies, so long as voltage is above the point at which shutdown occurs.

LTCs -- Though not a load component, LTCs on distribution substation transformers are not explicitly modeled in most power flow data bases, and thus, by default, become part of the load. As LTCs restore subtransmission and distribution voltages after a disturbance, they return the power flowing to voltage-sensitive devices to pre-disturbance levels. The increasing load can bring on voltage instability, deplete synchronizing power margins, or degrade damping. LTCs typically begin moving about one minute after a drop in voltage, and complete the restoration of voltage within another one to two minutes.

System Structure Considerations

The system structure is less important than the type of problem being analyzed. For instance, voltage stability problems can occur in any type of system, and load response to low voltage will be important regardless of the system structure.

Systems with long transmission distances or weak interconnections are most susceptible to synchronizing power and damping problems. Voltage response of loads will be important when synchronizing power margins are being considered. In systems with damping problems, frequency excursions will be large near machines that have the greatest participation in the particular mode of oscillation. Voltage excursions will be large at intermediate points between opposing machines or groups of machines. Therefore, the response of loads to both voltage and frequency will be important.

The first swing will be less sensitive to load characteristics in tightly coupled systems. In these systems a relatively severe fault is required to threaten stability, and the synchronizing power will be large and voltage excursions will be modest and short-lived. For these reasons, load characteristics will play only a minor role in the stability of tightly coupled systems.

In weakly coupled systems, voltage and frequency excursions will be large and synchronizing power will be modest. Loads thus will tend to play a significant role in first-swing behavior in such systems.

It is not always obvious when load characteristics are important in stability studies. A straight-forward procedure to assess sensitivity to load characteristics is to make comparative simulations with a range of load models. For instance, one may compare a constant impedance (active and reactive) load model with a constant current or constant power load model.

If a comparison of algebraic load models shows significant load effects, a more thorough evaluation using dynamic models for motors may be warranted. Some portion of the load, typically 50% to 70%, can be replaced with motor models. The motor model should be based on typical induction motor data and have a load torque proportional to speed (average of pump and conveyer characteristics). It is not necessary to include dynamic motors in every bus load, so long as the desired portion of total load in an area is represented as motors.

Load Composition

Load characteristics can vary significantly with time of day, day of week, season, and weather. It may be prudent in some studies to assume the worst-case load model for the problem under study. However, determining the worst-case load model may not be a trivial task. It may be necessary to build a range of load models and test each.

In warm climates, summer load may include large amounts of air conditioning load. Winter loads may consist of electric heating in areas of low energy cost, or heat pumps in other areas. Where fossil fuels are the primary source of winter space heating, there will be a component of motor load driving air handlers and fuel oil pumps.

Both air conditioning and heating loads are seasonal, but are also very sensitive to weather. Cold, windy weather will increase heating load and hot, humid weather will increase air conditioning load.

Weekday load is likely to be dominated by industrial loads. Up to 95% of the load in some industrial plants is motor load. Some process plants work around the clock and through weekends.

Commercial building loads consist largely of air conditioning and discharge lighting. This component of load is largest during weekday business hours.

Light industry often includes significant electric heating devices (packaging, soldering, etc.). As noted earlier, this load is constant resistance in the short term but is continually returned to a constant power level over a period of minutes.

Agricultural load consists largely of motors driving pumps, especially in growing seasons. Synchronous as well as induction motors may be used for this application.

Modeling Alternatives

Most present programs support one or more of the static load models described in Section 2, and dynamic induction motor models. Available dynamic motor models include those with rotor inertia and rotor flux transients represented and those with rotor inertia represented and electrical characteristics based on the motor equivalent circuit. The later type neglects rotor flux transients and thus may not always give sufficiently accurate results in first-swing and damping studies. The effective rotor circuit time constant of typical motors is in the range .05 to .15 seconds.

Some researchers have investigated the relationship between voltage and active and reactive load power, and a useful body of information on load-voltage characteristics exists. However, few investigations of the response of composite loads to frequency variations have been done. New models or improvements in existing models may be indicated by such tests.

Development of special models may be warranted for large unique loads such as aluminum smelters, chlorine plants, pumping plants, and steel mills.

An efficient composite load model may be useful. Presently all load components can be modeled individually by detailed dynamic load models, but these models greatly increase simulation times. An efficient load model might accept directly the output of the EPRI LOADSYN program and provide the appropriate dynamic characteristics for the study underway. Running time would be reduced, for instance, by neglecting frequency effects in voltage stability studies that do not involve significant frequency variation.

6. LOAD MODEL APPLICATION GUIDELINES

Simple static models may be adequate where parametric cases show such models give the same study results as more detailed dynamic models. Comparison of simple models and detailed models using typical data in both cases may be taken as a first step in the comparison. Where detailed load models are shown to be necessary, the typical data should be replaced by data based on best estimates of actual load device characteristics or test results.

The threshold of significance for differences in study results caused by load model changes will depend on the engineer's point of view. His point of view may be strongly influenced by his study objective and the engineering and computer time that is available to achieve it. Major factors will include the time required to gather the initial data for detailed models, the annual update effort, the data handling effort during a study (e.g., when changing from summer to winter conditions), and the power flow and simulation program running times. A planner may be less worried about accuracy on the one hand (especially if he's looking 10 years into the future), but also have the time to prepare and use detailed models. Operating studies may need high precision to set actual day to day transfer limits, but be constrained by the computer time available and the power flow or stability program running time (which will be longer with detailed load models). The engineer investigating a major disturbance will probably have the greatest need for accuracy, and may also have the time to achieve it. In each case, the engineer must evaluate his requirements and resources, and choose an appropriate compromise.

Use load models that accurately reflect specific load types when large special loads, such as chlorine plants, aluminum reduction plants, smelters, and electric furnaces, are in a part of the network that will experience significant voltage or frequency excursions.

Power plant auxiliaries, including adjustable speed drives should be modeled in detail in transient stability studies, especially in areas where faults will be placed. Because of the frequency variations that occur near generating plants during oscillations, plant auxiliary induction motors may be as important as motors in industrial plants.

Saturation effects in transformers, motors, and customer loads are important in simulations involving transients connected with loss of load or system breakup and consequent high voltages.

To ensure accuracy, stability studies should employ good dynamic load models. The load model should include the effects of motor inertia, motor rotor flux transients, contactor drop-out, discharge lighting discontinuities, and similar phenomena. Tailored load models should be used for large special loads such as aluminum reduction plants. The effects of LTCs on load magnitude in the minutes after a disturbance should be taken into account in damping and voltage stability studies. Synchronizing power and voltage stability studies should take into account the longer-term characteristics of loads. The effects of thermostats and LTCs and manual intervention by the customer are examples.

7. DATA FOR LOAD MODELING

There are two basic approaches to obtaining data on composite load characteristics. One is to directly measure the voltage and frequency sensitivity of load P and Q at representative substations and feeders. The other is to build up a composite load model from knowledge of the mix of load classes served by a substation, the composition of each class and typical characteristics of each load component. Each of these approaches has advantages and disadvantages, and each is described in more detail below. In general both should be used, as they are complementary, in order to understand and predict load characteristics under varying conditions.

Measurement-Based Data

Data for load modeling can be obtained by installing measurement and data acquisition devices at points where "bus loads" are to be represented. These devices must measure voltage and frequency variations and the corresponding variation in active and reactive power, either in response to intentional disturbances or to naturally-occuring events. These systems can also perform the function of disturbance data acquisition.

Several utilities have been developing systems to gather such data [2,13,21]. A new generation of such devices is being developed under the name of "disturbance monitors" [19,20,25].

One such system developed at IREQ has been operating at a Hydro-Quebec substation since May, 1989 [25]. It consists of a substation resident unit, which monitors voltages and currents continuously and a central computer which can control and retrieve data from several substation resident units. Optionally, when there are no disturbances, the mean and covariance of the voltage phasor, current phasor and frequency deviation over several minutes are computed and stored on a continuous basis. These may be used for small signal modeling purposes.

A microprocessor-based transient data recording system has been developed at Taipower company to investigate actual load behaviors during system disturbances [21]. At the present time, nine sets of self-acting monitoring system are installed at the level of primary substations and distribution substations of the Taipower system. The locations were selected at substations which supply power predominantly to residential loads, commercial loads, or industrial loads. When a system disturbance occurs, small or large, the recorders at each substation trigger automatically to record the three-phase voltages and currents onto a local computer. A digital sampling technique is used to record voltages and currents at the substation. The Discrete Fourier Transform technique is used to transform the recorded data into a phasor form. The voltage and current phasors at each substation are then used to compute both the real and reactive power at the substation. Since June 1988, several disturbances caused by either short-circuit faults or generator trip accidents have been detected by the load transient recorder system. The data are being used to identify parameters for both static and dynamic load models.

The parameters of a load model are estimated by fitting these data to the assumed model. The determination of static load model parameters from staged step changes in voltage are straightforward. Sophisticated estimation techniques may be needed to obtain more complicated models and to obtain models from data obtained during naturally-occuring disturbances. The data from such disturbances are beginning to be available. These data are expected to provide new information on the load characteristics.

Measurement-based techniques have the obvious advantage of obtaining data directly from the actual system. However, there are several disadvantages, including:

- Application of data gathered at one substation to load models for other substations may only be possible if the loads are very similar,
- Determination of characteristics over a wide range of voltage and frequency may be impractical,
- Accounting for variation of load characteristics due to daily, seasonal, weather, and end-use changes requires on-going measurements under these varying conditions.

One way of overcoming the first disadvantage is to use the approach reported by Ontario Hydro in Reference [9]. Measurements were made on feeders supplying specific classes of loads, e.g., residential, commercial, industrial, etc., to obtain typical characteristic data for each load class. These characteristics were then combined according to the mix of different load classes present at each bus. Measured static characteristics for different load classes at Ontario Hydro appear in Reference [9]. These tests were repeated for other system conditions to enhance the accuracy of the Load Class Characteristics and the derived load models. The Load Class Mix data required for this approach is the same as required for the component-based approach discussed below.

Component-Based Data

The purpose of the the component-based approach is to develop load models by aggregating models of the individual components forming the load. Component characteristics, e.g., for air conditioners, fluorescent lights, etc., can be determined by theoretical analysis and laboratory measurements and, once determined, used by all utilities. Much of this data has been determined and documented by EPRI projects [1,3,12], although it needs to be updated for new and redesigned load devices.

Since it would be difficult to determine directly the number of each type of load component on each feeder and substation in a system, a simpler approach was devised in EPRI project RP849-7 [12,14]. This approach, illustrated by Figure 2, requires the following information:

1. Typical compositions (fractions of load consumed by each type of load component) of each of several load classes, e.g., residential, commercial, industrial,
2. Mix of load classes at each bus.

The EPRI LOADSYN program [14] provides an automated means of combining these data to obtain loads models of varying complexity in standard forms for commonly-used power system analysis programs.

The composition data will vary with seasonal, daily, and other factors. The EPRI Load Modeling Reference Manual [12] includes typical data on load compositions for several load classes, geographical regions, seasons, and heating fuels. This data, obtained from census and load research data, can be used as a first estimate by individual utilities. Procedures for gathering more specific load composition data are described in the manual.

The load mix data, which describe the percentage contribution of each load class to the total load, vary from bus to bus in the system. The load mix data are also dependent on time and weather, based on consumption patterns and the underlying composition of each class. These functionalities of the Load Mix Data make it difficult to identify with great certainty. It remains an area that deserves attention by utilities to set up standard methods for derivation and formats for communicating it. Development of models, such as those used for load forecasting, that would relate weather, time of day, day of week, and other factors to the relative consumptions of different load components in each load class, should be considered.

One of the sources available for identifying the load mix data is load consumption information recorded by utilities for other purposes. Utilities use data recorders to measure the power flows at many points in their systems. From these measurements they derive the consumption for each load or a group of loads. This information, which is updated every few minutes, is kept on computers files and therefore can easily be used for other purposes.

A method described in Reference [9] uses the customer billing data to identify the load mix data. The billing data contains energy consumption for each quarter of the year for each of several regions and types of loads. This information is being used by Ontario Hydro to obtain seasonal load mix data for use with the LOADSYN program.

The composition-based approach to load modeling has the advantage of not requiring field measurements and of being adaptable to different systems and conditions. Its main disadvantage is in requiring the gathering of load class mix, and perhaps load composition, data, which are not normally used by power system analysts. Further industry attention to devising standard forms and methods for collecting this data would ease this problem. Several utilities are actively pursuing this data collection.

Typical Data

Typical data has previously been published in a number of papers and reports. The most extensive compilations are found in Concordia and Ihara [6] and the reports on the EPRI RP849 projects [1,3,12].

Table I shows a set of static load characteristics for various load classes, geographical regions of North America, seasons, and principal heating fuel. This data was obtained from the EPRI LOADSYN program using the default load compositions and component characteristics distributed with that program. The parameters in the table are for a model of the following form:

$$P = P_o \left(V/V_o\right)^{Kpv} \left[1. + Kpf\,(f - f_o)\right]$$

$$Q = Q_o \left(V/V_o\right)^{Kqv} \left[1. + Kqf\,(f - f_o)\right]$$

Table I
Typical Load Voltage and Frequency Parameters

	p.f.	Kpv	Kqv	Kpf	Kqf
RESIDENTIAL:					
Elec. Heating					
Northeast					
Summer	.90	1.2	2.7	.7	-2.3
Winter	.99	1.7	2.6	1.0	-1.7
North-Central					
Summer	.90	1.1	2.6	.8	-2.3
Winter	.99	1.7	2.6	1.0	-1.7
South					
Summer	.87	.9	2.4	.9	-2.1
Winter	.97	1.5	2.5	.9	-1.8
West					
Summer	.92	1.3	2.7	.8	-2.2
Winter	.99	1.7	2.5	1.0	-1.5
Non-Elec. Heating					
Northeast					
Summer	.91	1.2	2.8	.7	-2.3
Winter	.93	1.6	3.1	.7	-1.9
North-Central					
Summer	.91	1.3	2.8	.7	-2.2
Winter	.96	1.5	3.0	.8	-1.7
South					
Summer	.89	1.1	2.5	.9	-2.0
Winter	.97	1.6	2.9	.8	-1.6
West					
Summer	.94	1.4	2.9	.7	-2.1
Winter	.97	1.5	2.8	.9	-1.3
COMMERCIAL					
Elec. Heating					
Summer	.85	.5	2.5	1.2	-1.6
Winter	.90	.6	2.5	1.5	-1.1
Non-elec. Heating					
Summer	.87	.7	2.5	1.3	-1.9
Winter	.90	.8	2.4	1.7	-0.9
INDUSTRIAL	.85	.1	.6	2.6	1.6
PRIMARY ALUMINUM	.90	1.8	2.2	-0.3	.6
STEEL MILL	.83	.6	2.0	1.5	.6
POWER PLANT AUX.	.80	.1	1.6	2.9	1.8
AGRICULTURAL PUMPS	.85	1.4	1.4	5.6	4.2

In the absence of any further information on the load composition, the most commonly accepted static load model is to represent active power as constant current and reactive power as constant impedance. The constant current active power represents a mix of resistive and motor (nearly const. MVA) devices. This representation may be shifted more towards constant impedance or constant MVA, if the load is known to be more resistive or more motor-driven, respectively. This representation for an average load is reasonably well supported by the data in Table I.

8. VALIDATION OF LOAD REPRESENTATION

Though the sophistication of load modeling in dynamic simulations has improved greatly over the past several years, many utilities still face the difficult question of deciding which load models to employ to best represent their system load performance. Connected with this is the need to validate the models that are chosen and the data obtained by one of the methods discussed above. Two main approaches have been considered for load model validation. One is to make measurements directly at load substations in the same manner as described in Section 7. The other approach, based on system-wide measurements, is described below.

To address the question of load model validation, the Empire State Electric Energy Research Corporation (ESEERCO) in 1986 initiated a research project (EP86-7) with the goal of evaluating the sensitivity of New York Power Pool (NYPP) dynamic simulations to load modeling and validating the load models that are used in NYPP studies. The technique employed to validate the load model involves the comparison of simulated responses of important system variables to recorded data for system disturbances.

A digital acquisition system (DAS) is being developed for installation at ten critical stations within the NYPP system to provide the measured data. Measured responses to severe disturbances will be analyzed and compared with simulations using load models of varying complexity. The comparison is based on fourier-derived modes of oscillation and damping factors; thus exact time synchronization is not a requirement of the DAS units. The data captured by the DAS must be sufficient to compare with a 10-15 second simulation.

The DAS is designed to perform as a remote, unattended device which is capable of communicating with a master processing unit (MPU). Data transfer occurs via standard telephone lines. From the MPU, the engineer may examine and evaluate recorded data as well as modify the various operational parameters such as the channel trigger settings, scale factors, amount of pre-trigger data stored etc. The DAS itself is provided with 14 input channels to store station voltage and frequency as well as MW and MVar line flows. A sampling rate of 15 Hz is employed and storage capability is such that approximately 50 events of 30 seconds duration may be stored. A disturbance index file is maintained which contains the date and time of the event as well as the channel which initiated the trigger. The DAS provides the user with a choice of two trigger algorithms, a fixed value trigger and a moving range trigger whose limits will vary slowly with changing system conditions. The trigger settings may be easily modified from the MPU. One challenge in analyzing the measured results is to account for system changes that may result from the disturbance, such as removal of portions of the system, including loads, by relay action.

The advantage of the system-wide approach to model validation is that, if successful, it validates not only the load models but all of the models used in the analysis procedure. However, if discrepancies are found between measured and computed responses, it may be difficult to determine the source of the problem. It is therefore recommended that model validation include both system-wide comparisons and measurement on individual loads and other system equipment.

9. CONCLUSIONS

This paper has reviewed the state of the art of load representation for dynamic performance analysis. It is concluded that considerable progress has been made in recent years in understanding load characteristics and, particularly, in methods for determining improved load model data.

It is recommended that serious attention be given by power system analysts to the load models and data used in their studies. Steps should include:

1. Familiarization with recent literature, including references listed below.
2. Selection of most realistic models for near-term use, based on available data.
3. Investigation of possible existing sources of data on system load characteristics, such as billing data, load research studies, and system disturbance monitors.
4. Development of a plan for acquisition of improved load data, either through measurements or load mix/composition analysis.

There are a number of areas where further research and development are needed, including:

- Models and data for load behavior at low voltages and over long time periods, including self-tripping mechanisms for loads under low voltage conditions,
- Improved simplified modeling of induction motor characteristics, including saturation, frequency dependency, and low voltage stall, trip, and recovery behavior,
- Updated models and component characteristics for new and redesigned end-use devices,
- Standardized procedures for collecting load class mix data within utility organizations,
- Procedures and formats for exchange of load model data, including between electric power retailers and wholesalers.
- Procedures for modeling the impact of weather, daily, seasonal, and other factors on load composition,
- Improved understanding and modeling of the effect of subtransmission and distribution network elements (transformers, feeders, capacitors, etc.) on the aggregate load representation, including modeling of LTC transformers and of transformer saturation where important,
- Methods and equipment for measurements of load characteristics,
- Enhancements in the modeling options available in dynamic performance analysis computer programs, including discharge lighting, low-voltage motor behavior, and, for long-term dynamics, LTC transformer and dynamic (thermostatic) loads.

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