Power System Loads

Load Modelling

1. Basic load modelling concepts
2. Static load models
3. Dynamic load models
4. Induction motors
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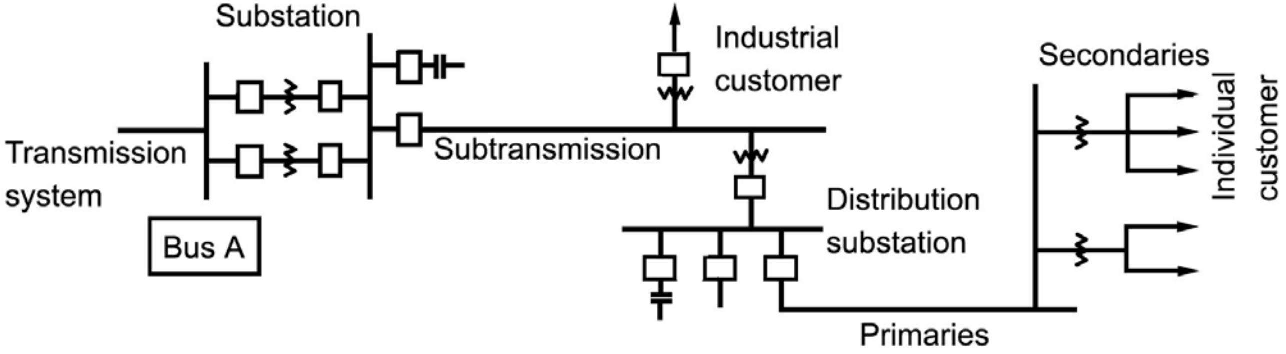
6. Acquisition of load model parameters

Load Modelling

- A typical load bus represented in stability studies is composed of a large number of devices:
  - fluorescent and incandescent lamps, refrigerators, heaters, compressors, furnaces, and so on
- The composition changes depending on many factors, including:
  - time
  - weather conditions
  - state of the economy
- The exact composition at any particular time is difficult to estimate. Even if the load composition were known, it would be impractical to represent each individual component.
- For the above reasons, load representation is based on considerable amount of simplification.

Basic Load Modelling Concepts

- The aggregated load is usually represented at a transmission substation
- includes, in addition to the connected load devices, the effects of step-down transformers, sub-transmission and distribution feeders, voltage regulators, and var compensation



Power system configuration identifying parts of the system represented as load at a bulk power delivery point (Bus A)

- Load models are traditionally classified into:
  - static load models
  - dynamic load models

Static Load Models

- Express the load characteristics as algebraic functions of bus voltage magnitude and frequency.
- Traditionally, voltage dependency has been represented by the exponential model:

$$P = P_0 \left(\frac{U}{U_0}\right)^a \qquad Q = Q_0 \left(\frac{U}{U_0}\right)^b$$

P_0, Q_0, and U_0 are the values of the respective variables at the initial operating condition.

- For composite loads,
  - exponent "a" ranges between 0.5 and 1.8
  - exponent "b" ranges between 1.5 and 6
- The exponent "b" is a nonlinear function of voltage. This is caused by magnetic saturation of distribution transformers and motors.

Alternative static models

- An alternative static model widely used is the *polynomial model*:

$$P = P_0\left(p_1\left(\frac{U}{U_0}\right)^2 + p_2\left(\frac{U}{U_0}\right) + p_3\right)$$

$$Q = Q_0\left(q_1\left(\frac{U}{U_0}\right)^2 + q_2\left(\frac{U}{U_0}\right) + q_3\right)$$

- This model is commonly referred to as the "**ZIP**" model, as it is composed of constant impedance (Z), constant current (I), and constant power (P) components.
- The frequency dependency of load characteristics is usually represented by multiplying the exponential or polynomial model by a factor:

For example,

$$P = P_0\left(p_1\left(\frac{U}{U_0}\right)^2 + p_2\left(\frac{U}{U_0}\right) + p_3\right)\left(1 + K_{pf}\Delta f\right)$$

$$Q = Q_0\left(q_1\left(\frac{U}{U_0}\right)^2 + q_2\left(\frac{U}{U_0}\right) + q_3\right)\left(1 + K_{qf}\Delta f\right)$$

where Δf is the frequency deviation (f-f_0). Typically, K_{pf} ranges from 0 to 3.0, and K_{qf} ranges from -2.0 to 0.

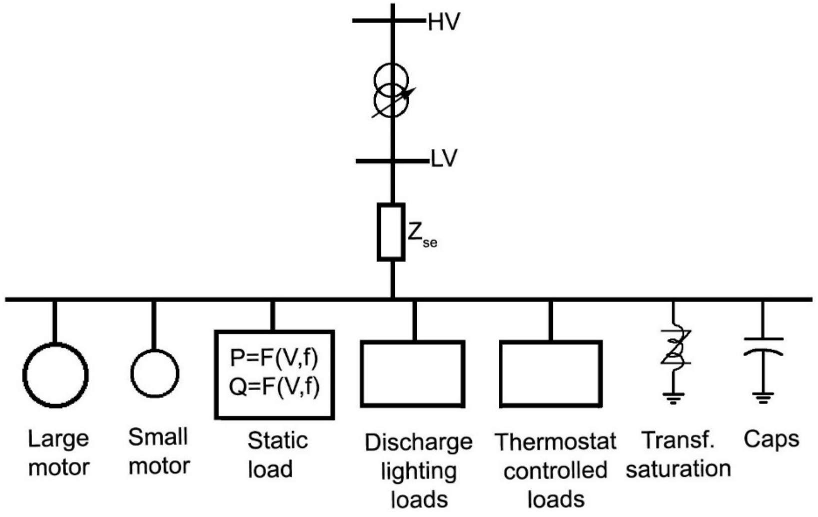
Response of most loads is fast and steady state reached quickly, at least for modest changes in V and f.

  - use of static model justified in such cases

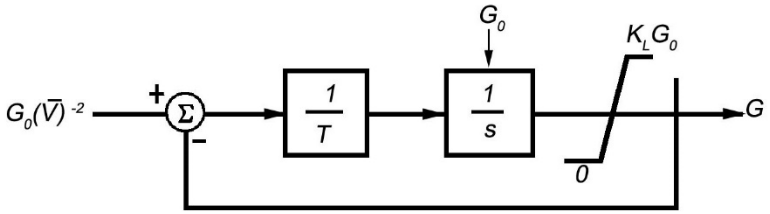
Dynamic Load Models

- In many cases, it is necessary to account for the dynamics of loads. For example, studies of
  - inter-area oscillations and voltage stability
  - systems with large concentrations of motors
- Typically, motors consume 60% to 70% of total energy supplied by a power system
  - dynamics attributable to motors are usually the most significant aspects
- Other dynamic aspects of load components include:
  - Extinction of discharge (mercury vapor, sodium vapor, fluorescent) lamps when voltage drops below 0.7 to 0.8 pu and their restart after 1 or 2 seconds delay when voltage recovers.
  - Operation of protective relays. For example, starter contactors of industrial motors drop open when voltage drops below 0.55 to 0.75 pu.
  - Thermostatic control of loads such as space heaters/coolers, water heaters and refrigerators - operate longer during low voltages and hence, total number of devices increase in a few minutes.
  - Response of ULTCs on distribution transformers and voltage regulators

- Composite model which represents the wide range of characteristics exhibited by various load components:



- A simple model for thermostatically controlled loads:



- The dynamic equation of a heating device may be written as:

$$K\frac{d\tau_H}{dt} = P_H - P_L$$

where

τ_H = temperature of heated area

τ_A = ambient temperature

P_H = power from the heater = $K_H G V^2$

P_L = heat loss by escape to ambient area = $K_A(\tau_H - \tau_A)$

G = load conductance

Induction Motor

- Carries alternating current in both stator and rotor windings
  - rotor windings are either short-circuited internally or connected through slip rings to a passive external circuit
- The distinctive feature is that the rotor currents are induced by electromagnetic induction.
- The stator windings of a 3-phase induction machine are similar to those of a synchronous machine
  - produces a field rotating at synchronous speed when balanced currents are applied
- When there is a relative motion between the stator field and the rotor, voltages and currents are inducted in the rotor windings
  - the frequency of the induced rotor voltages depends on the slip speed
- At no load, the machine operates with negligible slip. If a mechanical load is applied, the slip increases.

Modelling of Induction Motors

- The general procedure is similar to that of a synchronous machine
  - first write basic equations in terms of phase (a,b,c) variables
  - then, transform equations into 'dq' reference frame
- In developing the model of an induction motor it is worth noting the following of its features which differ from those of the synchronous machine:
  - rotor has a symmetrical structure; hence, d and q axis equivalent circuits are identical
  - rotor speed is not fixed; this has an impact on the selection of dq reference frame
  - there is no excitation source applied to the rotor; consequently the rotor circuit dynamics are determined by slip rather than by excitation control.
  - currents induced in shorted rotor windings produce a field with the same number of poles as in the stator; therefore, rotor windings may be represented by equivalent 3-phase winding

- The 'dq' transformation:
  - the preferred reference frame is one with axes rotating at synchronous speed, rather than at rotor speed
- The machine equations in dq reference frame:

- Stator flux linkages:

$$\Psi_{ds} = L_{ss} i_{ds} + L_m i_{dr}$$

$$\Psi_{qs} = L_{ss} i_{qs} + L_m i_{qr}$$

- Rotor flux linkages:

$$\Psi_{dr} = L_{rr} i_{dr} + L_m i_{ds}$$

$$\Psi_{qr} = L_{rr} i_{qr} + L_m i_{qs}$$

- Stator voltages:

$$V_{ds} = R_s i_{ds} - \omega_s \Psi_{qs} + p\Psi_{ds}$$

$$V_{qs} = R_s i_{qs} + \omega_s \Psi_{ds} + p\Psi_{qs}$$

- Rotor voltages:

$$V_{dr} = R_r i_{dr} - (p\theta_r)\Psi_{qr} + p\Psi_{dr}$$

$$V_{qr} = R_r i_{qr} + (p\theta_r)\Psi_{dr} + p\Psi_{qr}$$

The term $p\theta_r$ is the slip angular velocity and represents the relative angular velocity between the rotor and the reference *dq* axes

Representation of an Induction Motor in Stability Studies

- For representation in stability studies, $p\Psi_{ds}$ and $p\Psi_{qs}$ are neglected
  - same as for synchronous machines, this simplification is essential to ensure consistent models used for network and induction motors
- With the stator transients neglected, the per unit induction motor electrical equations may be summarized as:

Stator voltages in phasor form:
$$\boldsymbol{v}_{ds} + j\boldsymbol{v}_{qs} = \left(\boldsymbol{R}_s + j\boldsymbol{X}'_s\right)\left(\boldsymbol{i}_{ds} + j\boldsymbol{i}_{qs}\right) + \left(\boldsymbol{v}'_d + j\boldsymbol{v}'_q\right)$$

Rotor circuit dynamics:
$$p\left(v'_d\right) = -\frac{1}{T'_0}\left[v'_d + \left(X_s - X'_s\right)i_{qs}\right] + p\theta_r v'_q$$
$$p\left(v'_q\right) = -\frac{1}{T'_0}\left[v'_q - \left(X_s - X_s\right)i_{ds}\right] - p\theta_r v'_d$$

Rotor acceleration equation:
$$p\overline{\omega}_r = \frac{1}{2H}\left(T_e - T_m\right)$$
$$T_e = v'_d i_{ds} + v'_q i_{qs}$$

Synchronous Motor Model

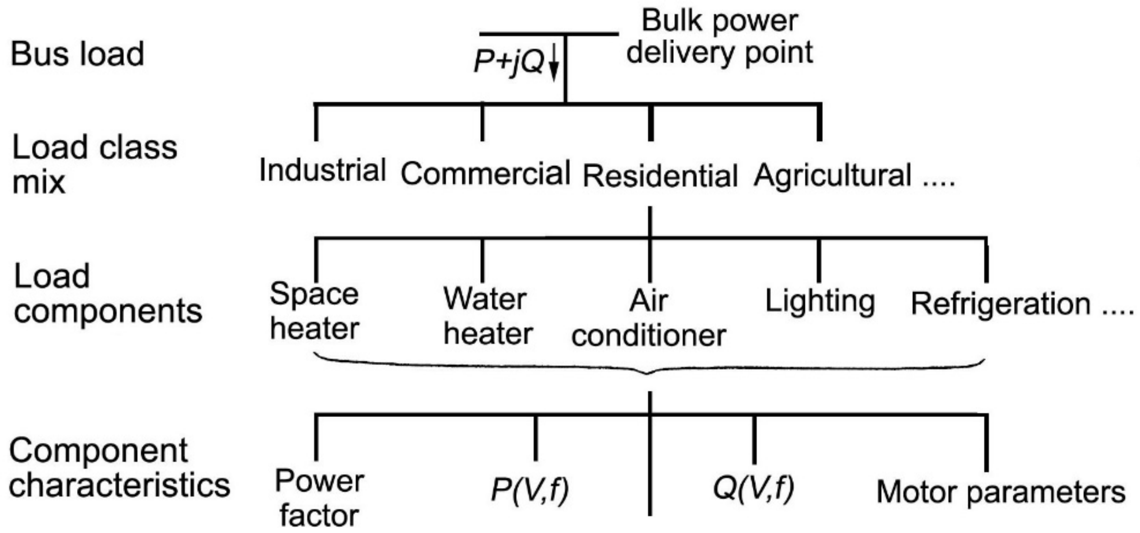
- A synchronous motor is modelled in the same manner as a synchronous generator
  - the only difference is that, instead of the prime mover providing mechanical torque input to the generator, the motor drives a mechanical load
- As in the case of an induction motor, a commonly used expression for the load torque is

$$T_m = T_0 \omega_r^m$$

Rotor acceleration equation is $$\frac{d\omega_r}{dt} = \frac{1}{2H}\left(T_e - T_m\right)$$

Acquisition of Load Model Parameters

- Two basic approaches:
  - measurement-based approach
  - component based approach
- Measurement-based approach
  - load characteristics measured at representative substations and feeders at selected times
  - parameters of loads throughout the system extrapolated from the above
- Component-based approach
  - involves building up the load model from information on its constituent parts
  - load supplied at a bulk power delivery point categorized into *load classes* such as residential, commercial, and industrial
  - each load class represented in terms of its components such as lighting, heating, refrigeration
  - individual devices represented by their known characteristics



- Composite load model derived by aggregating individual loads
    - EPRI LOADSYN program converts data on the load class mix, components, and their characteristics into the form required for stability studies

LOADSYN Program

- Creates aggregated specific static models (ZIP) or dynamic models (ZIP plus induction motor)
- Is component based; the model parameters are derived from
  - load mix data: percentage of residential, commercial and industrial class in each load (user specified)
  - class composition: percentage of load components, e.g. heating, lighting, etc., in each class (default data provided for North America)
  - component characteristics: static and dynamic parameters of each component (default data provided)
- Default data corresponds to fast dynamics and small voltage excursions
- Load characteristics for voltage stability studies have not been investigated extensively
- Distribution ULTC and voltage regulation is not accounted for (therefore, ULTC models must be included in the system data)

Component Static Characteristics

Table 7.1 summarizes typical voltage and frequency dependent characteristics of a number of load components.

Table 7.1

Component	**Power Factor**	**$\partial P/\partial V$**	**$\partial Q/\partial V$**	**$\partial P/\partial f$**	**$\partial Q/\partial f$**
Air conditioner					
- 3-phase central	**0.90**	**0.088**	**2.5**	**0.98**	**-1.3**
- 1-phase central	**0.96**	**0.202**	**2.3**	**0.90**	**-2.7**
- window type	**0.82**	**0.468**	**2.5**	**0.56**	**-2.8**
Water heaters,	**1.0**	**2.0**	**0**	**0**	**0**
Range top, oven					
Deep fryer					
Dishwasher	**0.99**	**1.8**	**3.6**	**0**	**-1.4**
Clothes washer	**0.65**	**0.08**	**1.6**	**3.0**	**1.8**
Clothes dryer	**0.99**	**2.0**	**3.2**	**0**	**-2.5**
Refrigerator	**0.8**	**0.77**	**2.5**	**0.53**	**-1.5**
Television	**0.8**	**2.0**	**5.1**	**0**	**-4.5**
Incandescent lights	**1.0**	**1.55**	**0**	**0**	**0**
Fluorescent lights	**0.9**	**0.96**	**7.4**	**1.0**	**-2.8**
Industrial motors	**0.88**	**0.07**	**0.5**	**2.5**	**1.2**
Fan motors	**0.87**	**0.08**	**1.6**	**2.9**	**1.7**
Agricultural pumps	**0.85**	**1.4**	**1.4**	**5.0**	**4.0**
Arc furnace	**0.70**	**2.3**	**1.6**	**-1.0**	**-1.0**
Transformer (unloaded)	**0.64**	**3.4**	**11.5**	**0**	**-11.8**

Load Class Static Characteristics

Table 7.2 summarizes the sample characteristics of different load classes.

Table 7.2

Load Class	Power Factor	∂P/∂V	∂Q/∂V	∂P/∂f	∂Q/∂f
Residential					
- summer	**0.9**	**1.2**	**2.9**	**0.8**	**-2.2**
- winter	**0.99**	**1.5**	**3.2**	**1.0**	**-1.5**
Commercial					
- summer	**0.85**	**0.99**	**3.5**	**1.2**	**-1.6**
- winter	**0.9**	**1.3**	**3.1**	**1.5**	**-1.1**
Industrial	**0.85**	**0.18**	**6.0**	**2.6**	**1.6**
Power plant auxiliaries	**0.8**	**0.1**	**1.6**	**2.9**	**1.8**

Dynamic Characteristics

The following are sample data for induction motor equivalents representing three different types of load (see Fig. 7.7 for definition of parameters).

(i) The composite dynamic characteristics of a feeder supplying predominantly a commercial load:

$R_s = 0.001$ $X_s = 0.23$ $X_r = 0.23$

$X_m = 5.77$ $R_r = 0.012$ $H = 0.663$ $m = 5.0$

(ii) A large industrial motor:

$R_s = 0.012$ $X_s = 0.07$ $X_r = 0.165$

$X_m = 3.6$ $R_r = 0.01$ $H = 1.6$ $m = 2.0$

(iii) A small industrial motor:

$R_x = 0.025$ $X_s = 0.10$ $X_r = 0.17$

$X_m = 3.1$ $R_r = 0.02$ $H = 0.9$ $m = 2.0$