ECE 522 - Power Systems Analysis II
Spring 2021

Load Modeling

Spring 2021

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Content

1. Chapter 7 of Kundur's book
2. Load Performance for Dynamic Performance Analysis, IEEE Committee Report, IEEE Trans. on Power Systems, Vol. 8, No. 2, pp. 472-482, May 1993.
3. Bibliography on Load Models for Power Flow and Dynamic Performance Simulation, Vol. 10, No. 1, pp. 523-538, Feb. 1995.
4. Standard Load Models for Power Flow and Dynamic Performance Simulation, IEEE Trans. on Power Systems, Vol. 10, No. 2, pp. 1302-1313, Aug. 1995
5. EPRI Report: Load Modeling for Power Flow and Transient Stability Computer Studies, Vol. 2: Load-Modeling Reference Manual, Product ID: EL-5003-CCMV2, 1987 http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=EL-5003-CCMV2
6. EPRI Report: Measurement-Based Load Modeling, Product ID:1014402, 2006 http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001014402
7. A. Bokhari et al., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads," IEEE Trans. Power Deliv., vol. 29, no. 3, pp. 1372–1381, Jun. 2014,

Background

- The representation of loads has not received as much attention as other components in power systems, but it may have significant impacts on stability analysis results.
- Accurate load modeling is difficult because:
  - at high-voltage levels, loads must be aggregated for stability studies,
  - a power system has a large number of diverse load components,
  - ownerships and locations of load devices are not directly accessible to the electricity utility (e.g. transmission and distribution are owned by different companies)
  - there is no precise information on load composition, which changes with time of day and week, seasons and weather, and
  - load characteristics are uncertain, particularly for large voltage or frequency variations

Bus Load

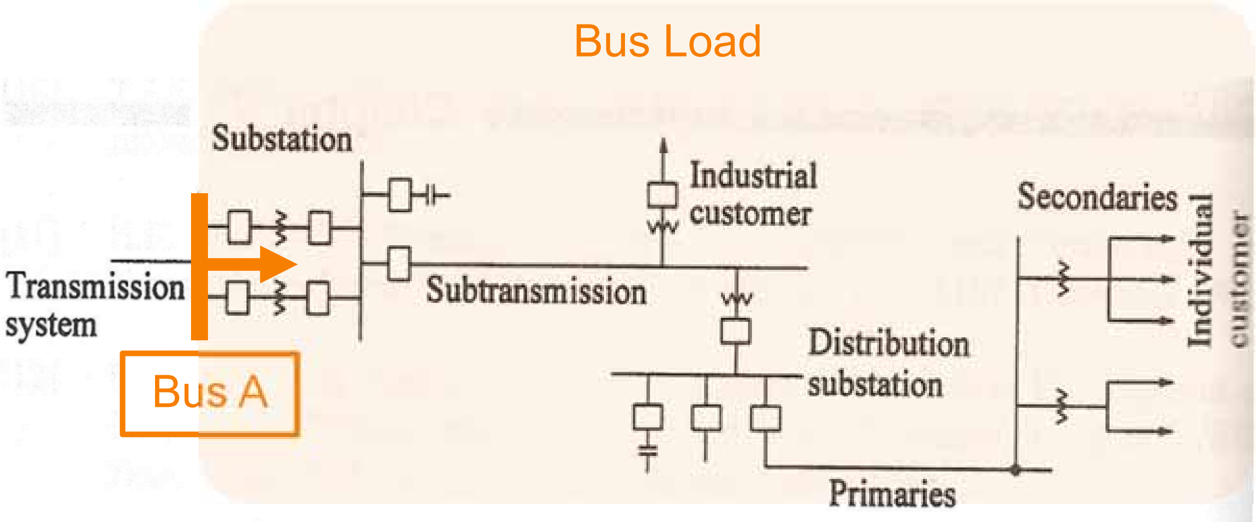


Figure 7.1 Power system configuration identifying parts of the system represented as load at a bulk power delivery point (bus A)

- Defined as a portion of the actual system, which is not explicitly represented in the system model but treated as a single power-consuming device connected to a bus in the system model

- In this context, "bus load" includes connected load devices together with some or all of the following:
  - Substation step-down transformers
  - Sub-transmission feeders
  - Primary and secondary distribution feeders
  - Distributions transformers
  - Shunt capacitors, voltage regulators
  - Customer wiring, transformers and capacitors

- If we want to represent the "bus load" accurately, those elements listed must be accounted for.

- For bulk power system studies, much of the sub-transmission as well as the distribution system are omitted.

Load Modeling

Objective: $I(V, f)$, or equivalently $P(V, f)$ and $Q(V, f)$

- "Top-down" (identification; **measurement-based approach**): Select a load model structure and then perform parameter estimation using an appropriate identification technique based on field measurements.

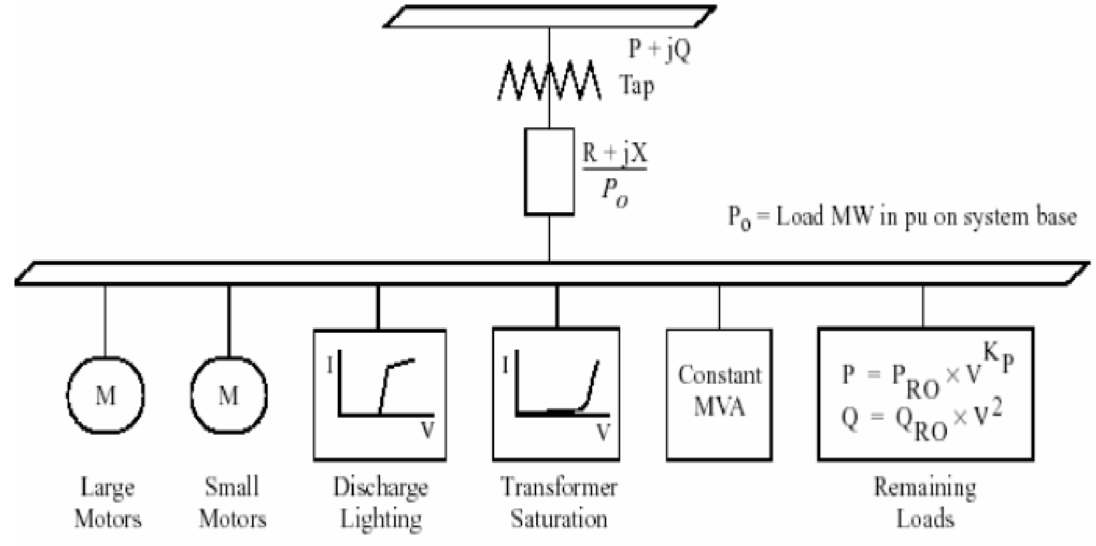


Figure 3-9
Composite Model (CLODBL) Model Used by PSS/E

- "Bottom-up" (theoretical aggregation; **component-based approach**): Analytically, by lump similar loads based on the load type and then use pre-determined values for each parameter of the load.

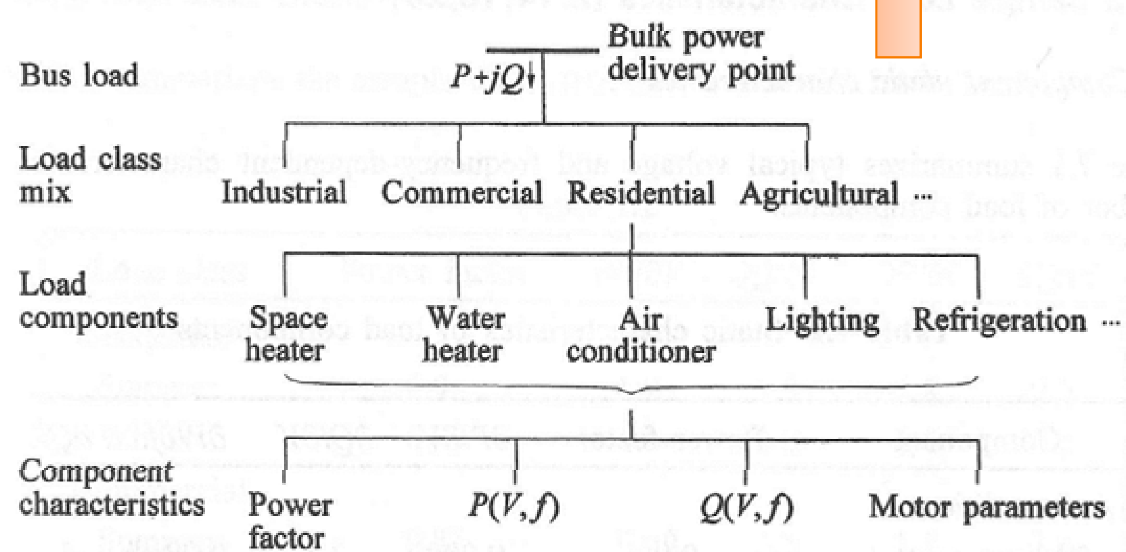


Figure 7.21 Component-based modelling approach

Component-based approach

Terminology

- Load Characteristics: A set of parameters or functions, e.g. power factor, $P(V, f)$ and $Q(V, f)$, describing behaviors of a specified load. This could be applied to either a specific load device or an aggregation of multiple load devices (e.g. a load component, a load class and the total bus load)
- Load Component: The aggregate equivalent of all load devices of similar types, e.g. heater, air conditioner, lighting, etc.
- Load Composition: Fractional composition of the load by Load Components
  - Could be fraction applied to a Bus Load or to a specific Load Class
  - As an example, composition for an internet data center could be 40-50% computer servers, 40-50% HVAC loads and 10-15% lighting loads

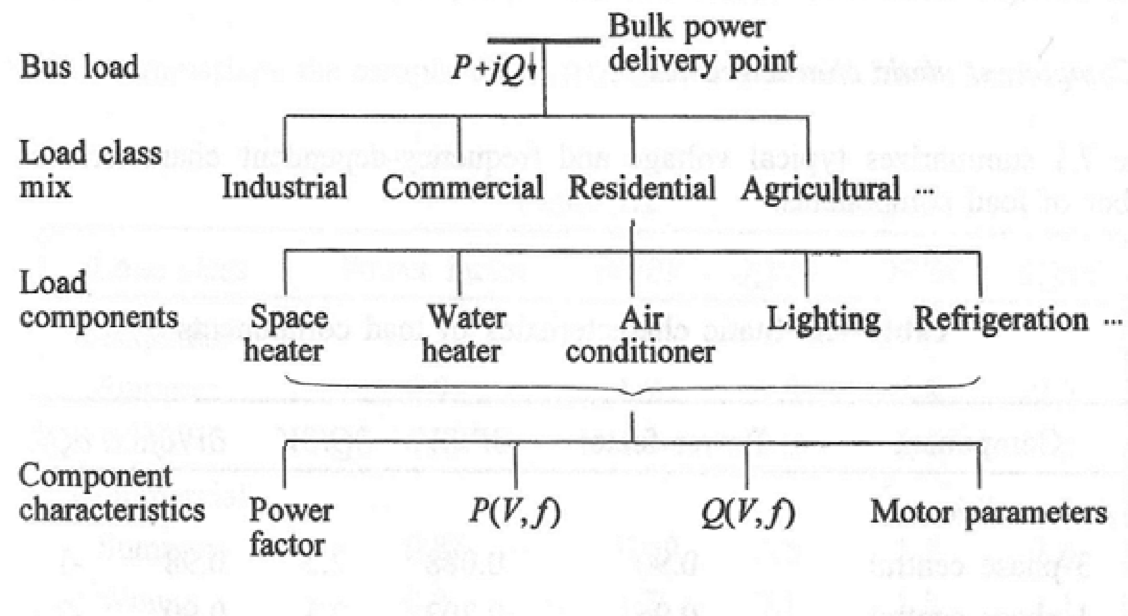
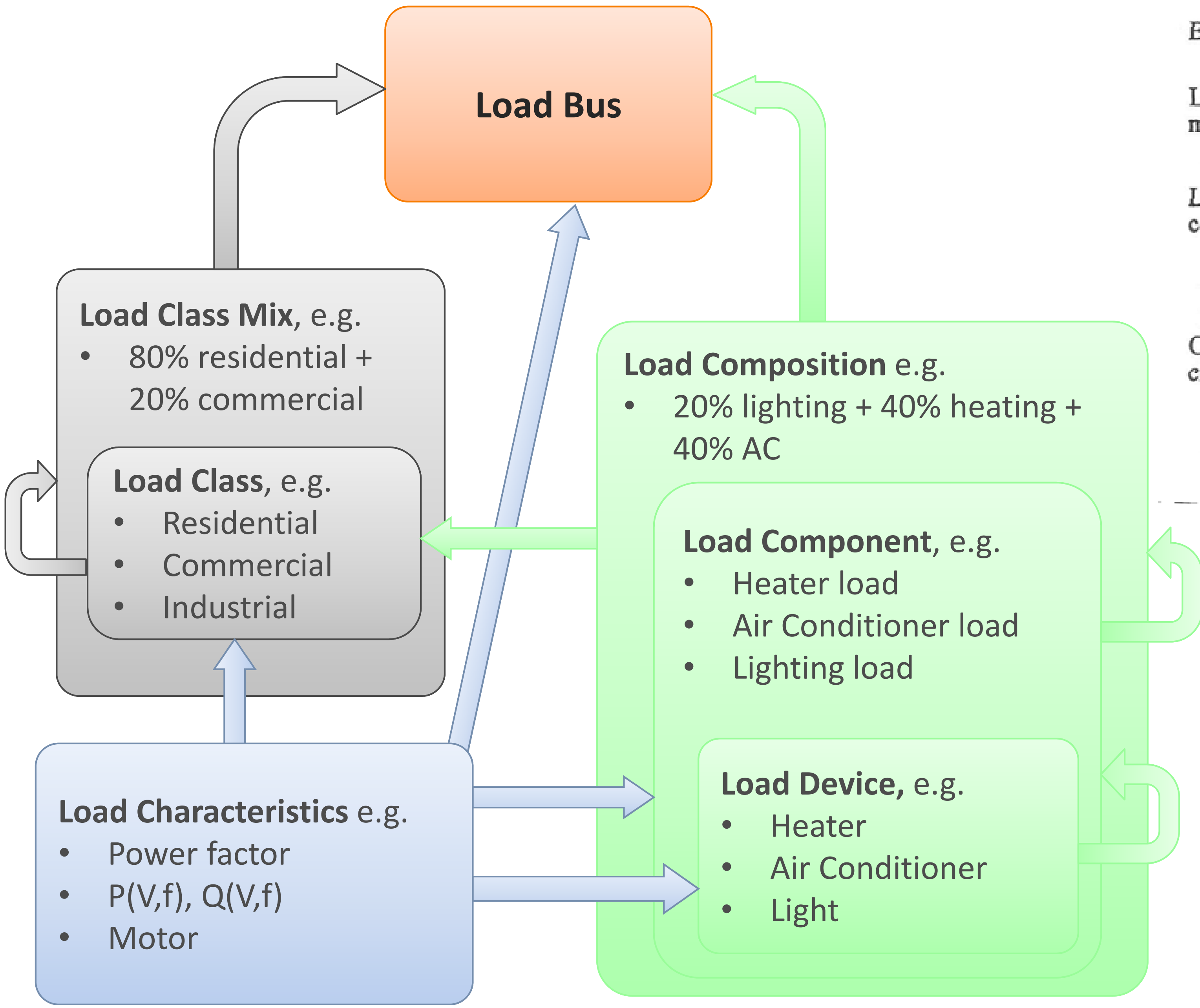


Figure 7.21 Component-based modelling approach

- Load Class: A category of load, e.g. residential, commercial or industrial. For load modeling purposes, it is useful to group loads into several classes, which each have similar load composition and characteristics
- Load class mix: Fractional composition of the Bus Load by Load Class.

Component-based approach



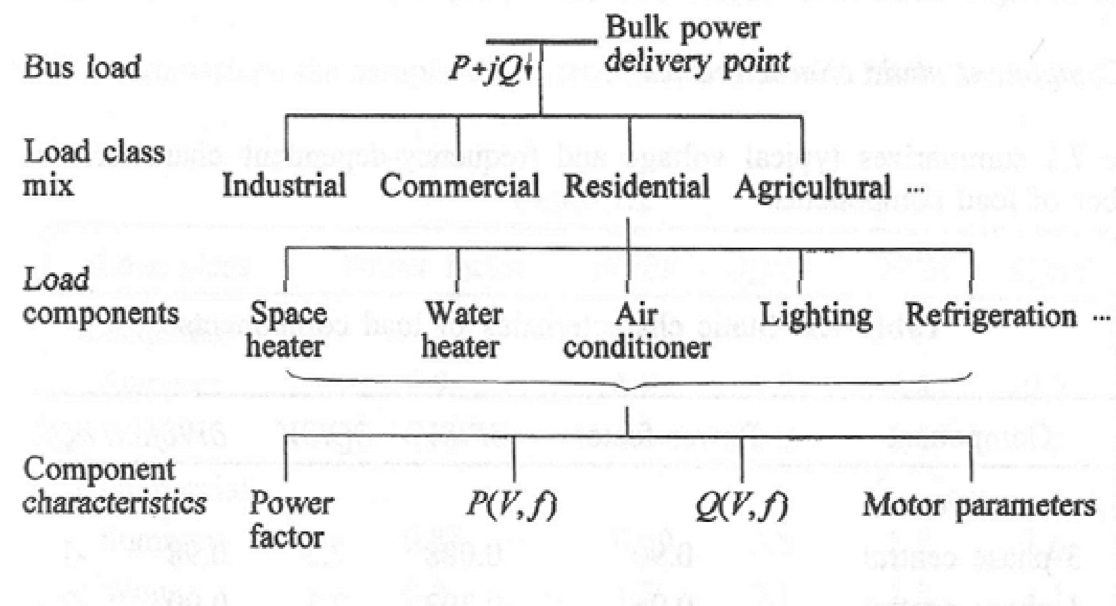


Figure 7.21 Component-based modelling approach

Load Models

- Static Load Model:
  - P and Q at time t are expressed as algebraic equations on values of bus voltage magnitude V and frequency f only at time point t.

    $P(V(t),\ f(t)\ )$

    $Q(V(t),\ f(t)\ )$

  - On resistive/ lighting loads or simplified dynamic loads

- Dynamic Load Model:
  - P and Q at time t are expressed as difference/differential equations on V and f at t and past time instants

    $P(\ V(\tau \leq t),\ f(\tau \leq t)\ )$

    $Q(\ V(\tau \leq t),\ f(\tau \leq t)\ )$

  - On induction motor loads and others

Static Load Models

- **Polynomial load model (ZIP Model):**

  P_0, Q_0 and V_0 are rated values or the values at the initial operating condition

$$\bar{V} = \frac{|V|}{V_0}$$

$$P = P_0(p_1\bar{V}^2 + p_2\bar{V} + p_3)$$

$$Q = Q_0(q_1\bar{V}^2 + q_2\bar{V} + q_3)$$

$p_1+p_2+p_3=1$ and $q_1+q_2+q_3=1$ if P_0, Q_0 and V_0 are rated values

Composed of three types of components:

constant impedance: Z ~ $1/(p_1\text{-j}q_1)$

constant current: $I \sim p_2\text{-j}q_2$

constant power: $P \sim p_3$ or $Q \sim q_3$

- **Exponential load model**

$$P = P_{0(\bar{V})}{}^{a}$$

$$Q = Q_{0(\bar{V})}{}^{b}$$

  - Estimation of a and b:

    Around V_0,

$$\frac{\partial\bar{P}}{\partial\bar{V}} \approx a \qquad \frac{\partial\bar{Q}}{\partial\bar{V}} \approx b$$

Value of a (or *b*)	Corresponding ZIP model
0	Constant power
1	Constant current
2	Constant impedance

Usually, *a*=0.5-1.8 and *b*=1.5-6.0

Frequency Dependency

- With a frequency deviation $\Delta f = f - f_0$

$$P = P_{0(\bar{V})}{}^{a}\left(1 + K_{pf}\Delta f\right)$$

$$Q = Q_{0(\bar{V})}{}^{b}\left(1 + K_{qf}\Delta f\right)$$

$$P = P_0(p_1\bar{V}^2 + p_2\bar{V} + p_3)\ (1 + K_{pf}\Delta f)$$

$$Q = Q_0(q_1\bar{V}^2 + q_2\bar{V} + q_3)\ (1 + K_{qf}\Delta f)$$

Typically, $K_{pf} = \partial P/\partial f =$ 0 to 3.0,

$K_{qf} = \partial Q/\partial f =$ -2.0 to 0

  - Note: Unlike the speed of a generator, the frequency of a bus voltage is not a state variable in the system model for stability analysis.
  - Δf can be computed by taking the numerical derivative of the voltage phase angle.

- Comprehensive static model: summation of ZIP and exponential models

$$P=P_0(P_{ZIP}+P_{EX1}+P_{EX2})$$

Typical Static Loads

Static Characteristics of Load Components

Component	Power factor	∂P/∂V a	∂Q/∂V b	∂P/∂f K_{pf}	∂Q/∂f K_{qf}
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,					
Range top, oven,	1.0	2.0	0	0	0
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

Static Characteristics of Load Classes

Load class	Power factor	∂P/∂V a	∂Q/∂V b	∂P/∂f K_{pf}	∂Q/∂f K_{qf}
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

$$P = P_0(\bar{V})^a(1 + K_{pf}\Delta f)$$
$$Q = Q_0(\bar{V})^b(1 + K_{qf}\Delta f)$$

Value of a (or *b*)	Corresponding ZIP model
0	Constant power
1	Constant current
2	Constant impedance

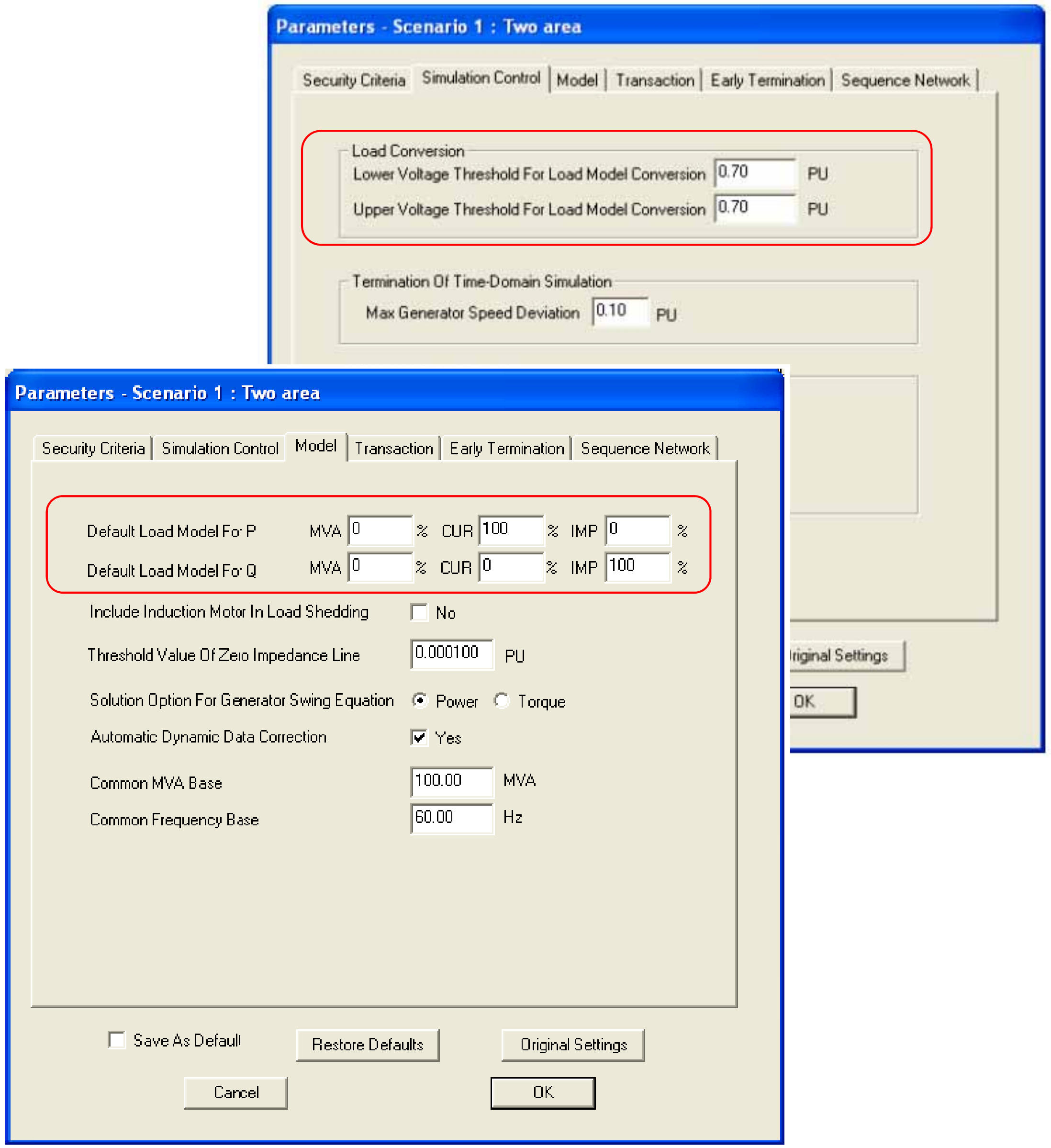
Static Load Modeling in Stability Studies (TSAT, PSS/E, etc.)

- In the absence of information on load characteristics:
  - When V is around V_0

    a=1: P as constant current

    b=2: Q as constant impedance

  - When V is below a threshold (e.g. 0.6-0.7V_0) , convert the entire bus load to a constant impedance load to avoid computational problems.



Thermostat-Controlled Loads

- Space heaters, water heaters, molding and packaging machines, soldering machines, etc.
- Such loads are dynamical but are conventionally modeled as static loads in stability studies:
  – Short term: constant resistance.
  – Long term: constant power with a suitable time constant.

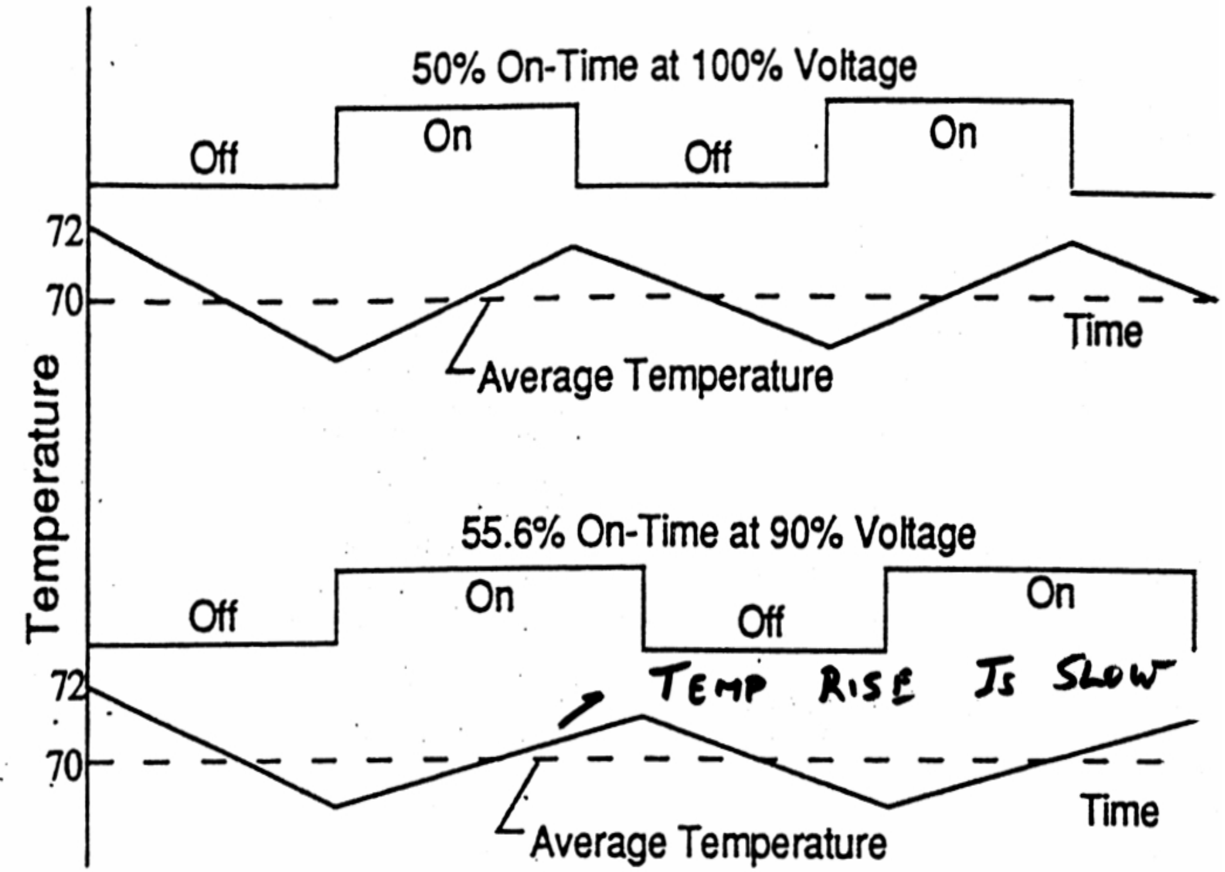
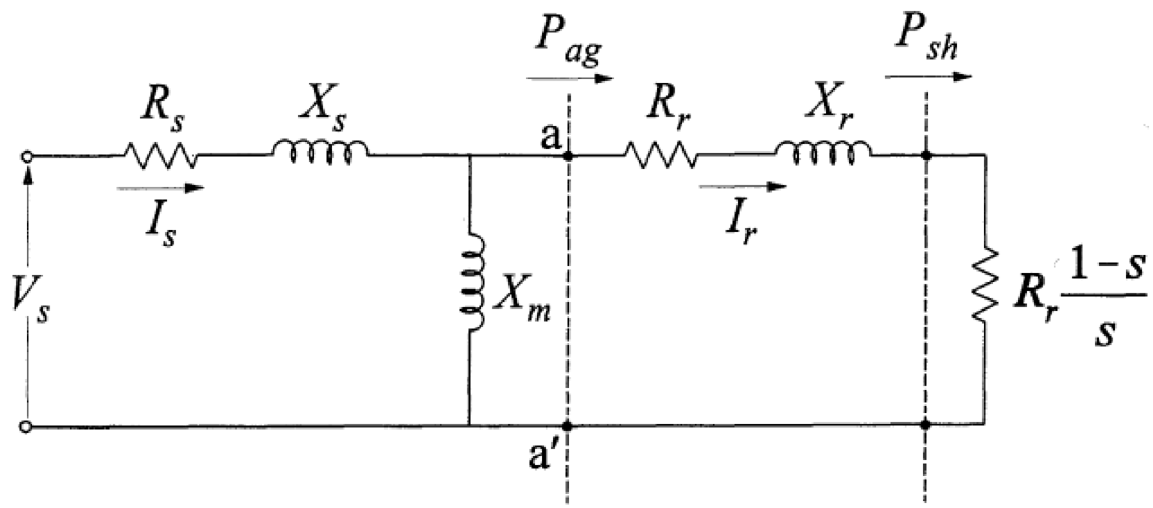


Figure 5. When voltage is low, thermostats on "resistance type loads" remain closed longer, effectively restoring the load to a constant power characteristic in the steady-state.

Motor loads

- Motor loads consume 60-70% of the total energy supplied by a power system.
- Motors could drop 70% of system load during a fault or during voltage excursions following the fault. This will improve (or impact) stability of receiving-end (or sending-end) generators
- Air-conditioner compressor induction motors count up to 50% of system load in summer
  - It stalls if the voltage is low (e.g. 50-65% of the nominal voltage for 3 cycles) due to a fault; once stalled, it behaves like a constant impedance load (with a low power factor) drawing 2-3 times of the rated current.
  - The thermal overload protection disconnects the motor if it remains stalled for considerable amount of time (typically, 15s if stalled at 50% voltage)
  - It recovers if voltage goes back to 70% of the nominal voltage. That delays the voltage recovery.
  - In areas with a high percentage of air conditioner loads, delayed voltage recovery (e.g. FIDVR issues), short-term voltage stability and fast voltage collapse are main stability concerns.

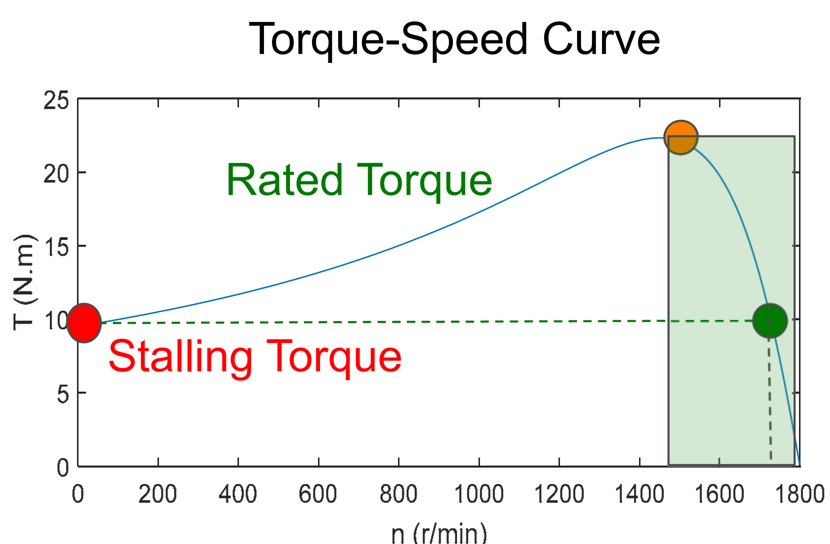
Modeling of Induction Motors

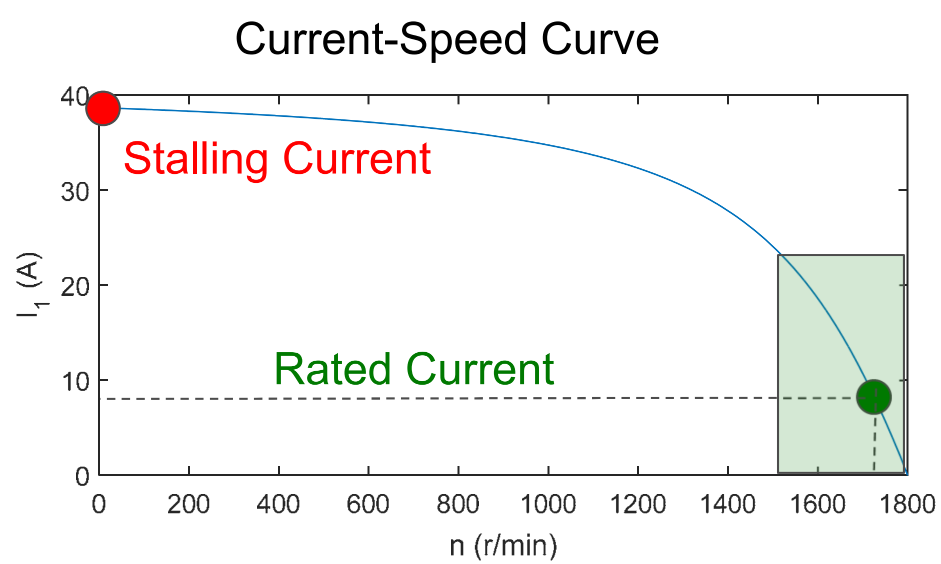


$$s = \frac{n_s - n_r}{n_s}$$

$$T \propto \frac{P_{sh}}{n_r}$$

Figure 7.8 Alternative form of induction machine equivalent circuit





Impacts on Angular and Voltage Stabilities

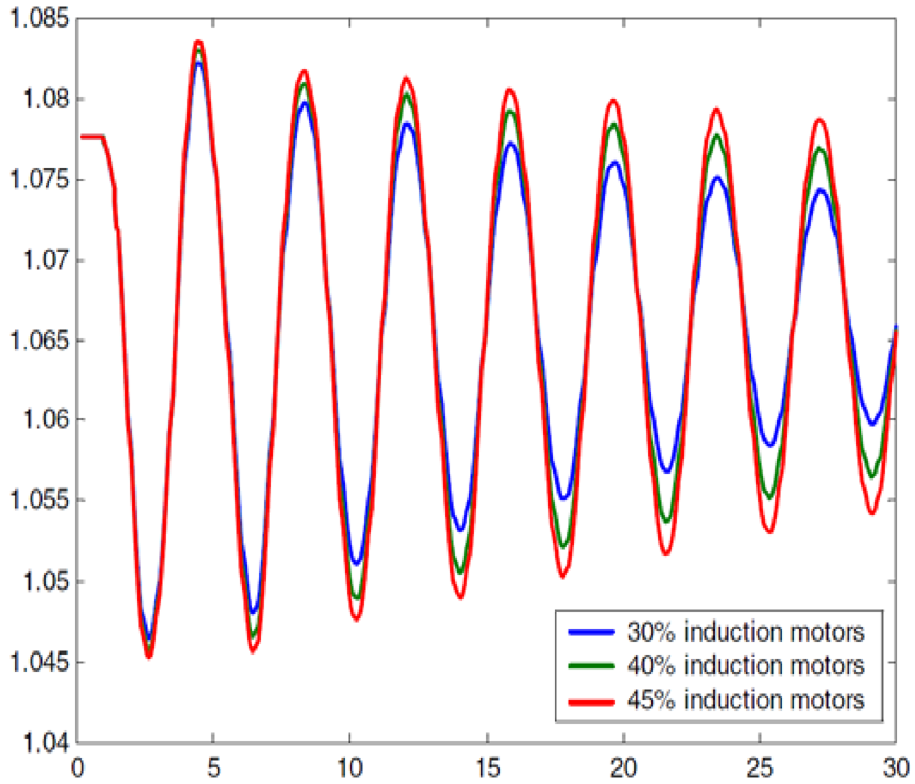
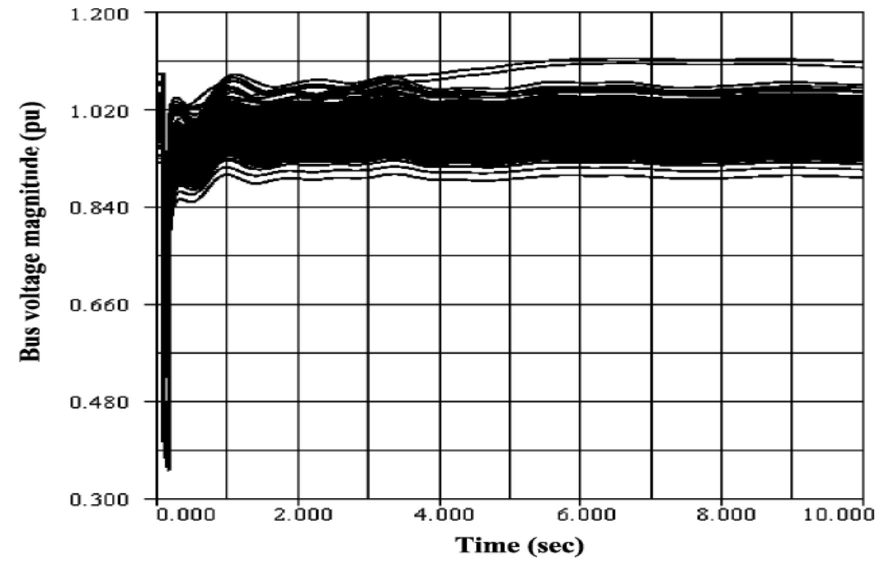
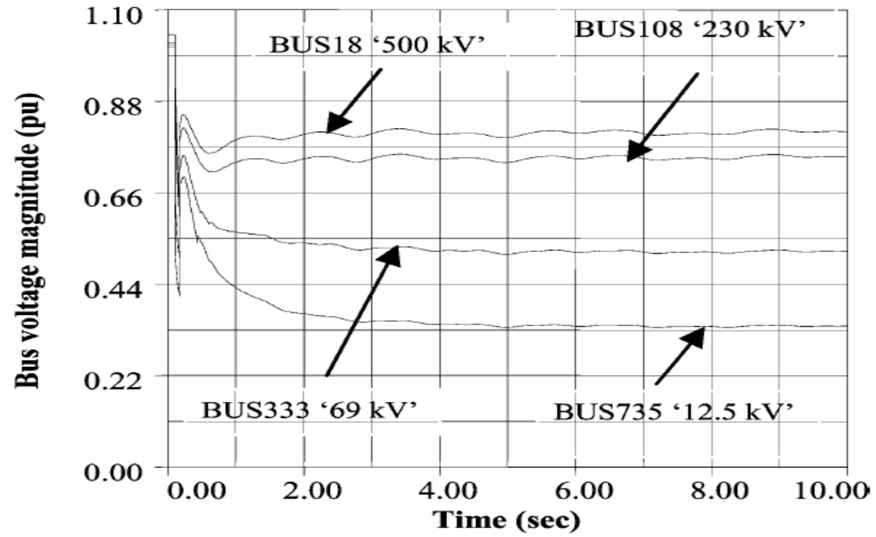


Figure 1-2
Impact of Induction Motors on System Oscillation

Without motor loads modeled



With motor loads modeled



Sources:

- *Measurement-Based Load Modeling, EPRI Report, Product ID:1014402, 2006*
- *B. Sapkota, et al, Dynamic VAr Planning in a Large power System Using Trajectory Sensitivities, IEEE Trans. Power Systems, Feb, 2010*

Measurement-based Approach for Load Modeling

- Load characteristics are measured at representative substations and feeders at selected times of days and seasons.
  - Steady-state $\partial P/\partial V$, $\partial P/\partial f$, $\partial Q/\partial V$, $\partial Q/\partial f$
  - Dynamic load-voltage characteristics

- Parameters of loads are estimated to optimally fit the measurements

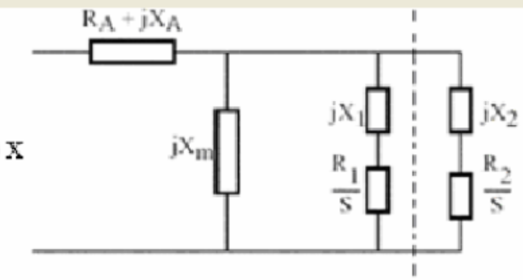
- Then, the estimated parameters are extrapolated for the entire system.

Table 6-16
Converged Parameters – ZIP + Motor Model Structure

Parameter Derivation Results

Load Model Configuration -ZIP static model + induction mot

$$a \times \begin{cases} P = P_0 \left[a_p \left(\frac{V}{V_0}\right)^2 + b_p \left(\frac{V}{V_0}\right) + c_p \right] (1 + k_p \Delta f) \\ Q = Q_0 \left[a_q \left(\frac{V}{V_0}\right)^2 + b_q \left(\frac{V}{V_0}\right) + c_q \right] (1 + k_q \Delta f) \end{cases} + (1\text{-}a) \times$$



$$k_p = k_q = 0 \quad c_p = 1 - a_p - b_p \quad c_q = 1 - a_q - b_q$$

Parameters for static load - P

Parameter	Initial Value	Derived Value	Deviation%
a	0.5	0.3216	-35.6735
ap	0.4	-5.5823	-1495.5869
bp	0.3	-2.1105	-803.5092

Parameters for static load - Q

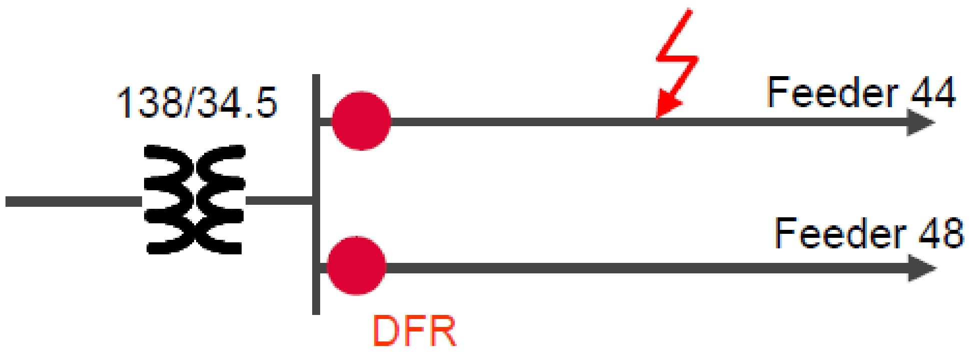
Parameter	Initial Value	Derived Value	Deviation%
a	0.5	0.9408	88.1551
aq	0.4	-12.2013	-3150.33
bq	0.3	-9.8494	-3383.1358

Parameters for dynamic (motor) load

Parameter	Initial Value	Derived Value	Deviation%
X1	0.16	0.4995	212.197
XA	0.12	0.4990	315.7978
XM	3.2	2.8958	-9.5074
R1	0.018	0.4996	2675.6405
RA	0.031	0.4999	1512.5899
A	1	0.8652	-13.4815
B	0	0.3934	Inf
D	0	0.0008	Inf
E	0	0.8841	Inf
H	0.7	0.1690	-75.8586
T	0.8622	0.4799	-44.339

Sources: Measurement-Based Load Modeling, EPRI Report, Product ID:1014402, 2006

Field Test



Measuring feeder current, voltage being monitored is bus voltage

Figure 6-48
Illustration for Fault and Data Collection Locations at a Substation

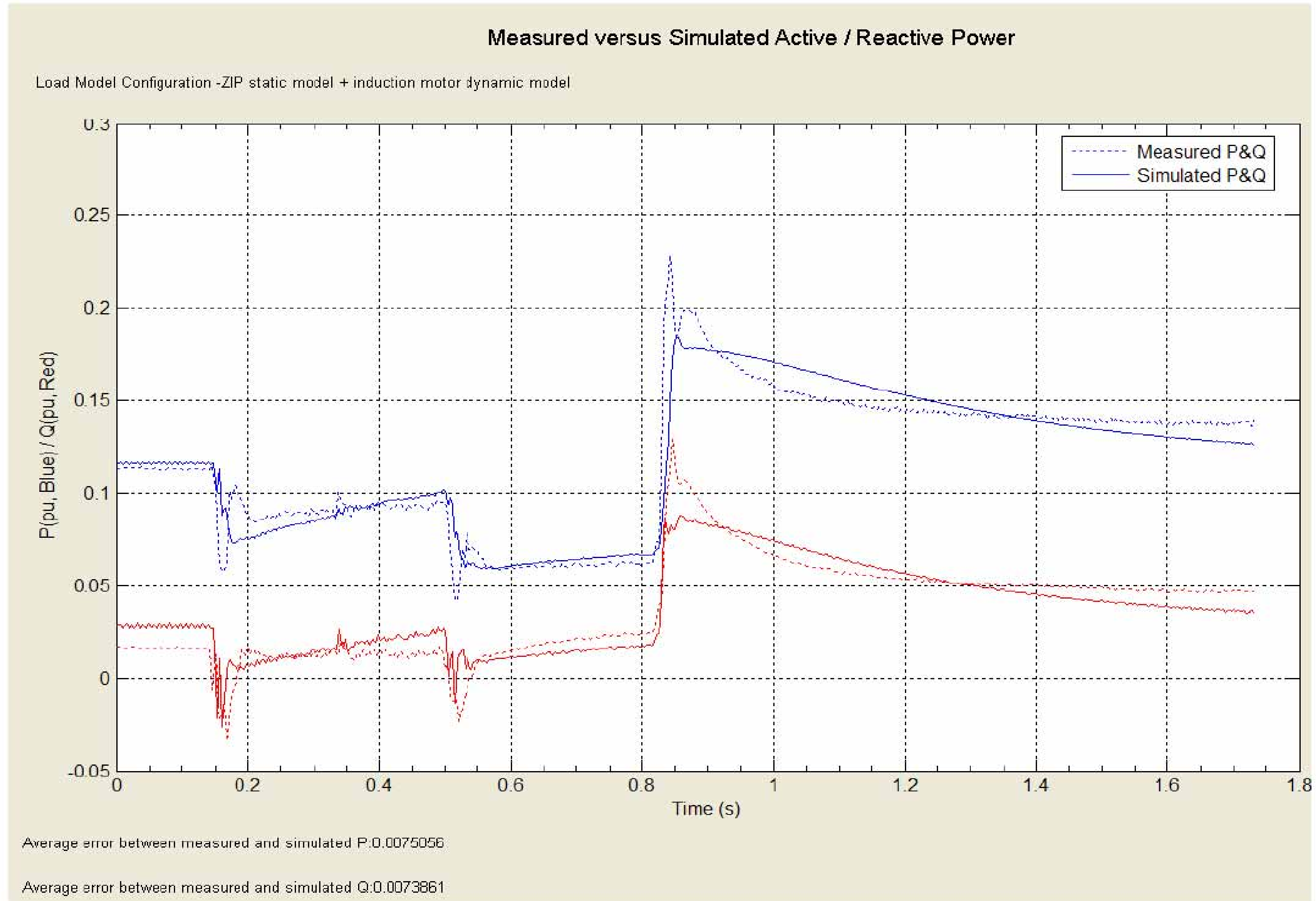


Figure 6-52
Comparison of Measured and Estimated (Using Converged Parameters) Real and Reactive Power – ZIP + Motor Model Structure