University of Exeter

Centre for Smart Grid

T2 ENGM031 Tutorial

Modelling of Power System Loads

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Introduction

- Power System engineers base decisions regarding system reinforcements and system performances on the results of power flows and stability simulation studies.

- Inadequacies in simulation models result in the under or over building of Power Systems, which can be financially costly and degrade the reliability of the system.

- For power system analysis studies models must be developed for all power system components including generators, transmission and distribution networks and LOADS.

- Load representation can have a significant impact on analysis results, consequently accurate load modelling is important. Accurate load modelling is a difficult task for several reasons:
  - large number of diverse load components
  - most loads are not directly accessible to the electric utility, they are a part of the customers facilities
  - composition of loads change with time of day and week, seasons, weather and industry/domestic/commercial evolution
  - lack of information on composition of loads
  - Uncertainties regarding the characteristics of many load components during large voltage or frequency variations.

- Utilities often collect information on load composition for load forecasting purposes. However, this information is often not accessible or in a usable form for system analysis purposes.

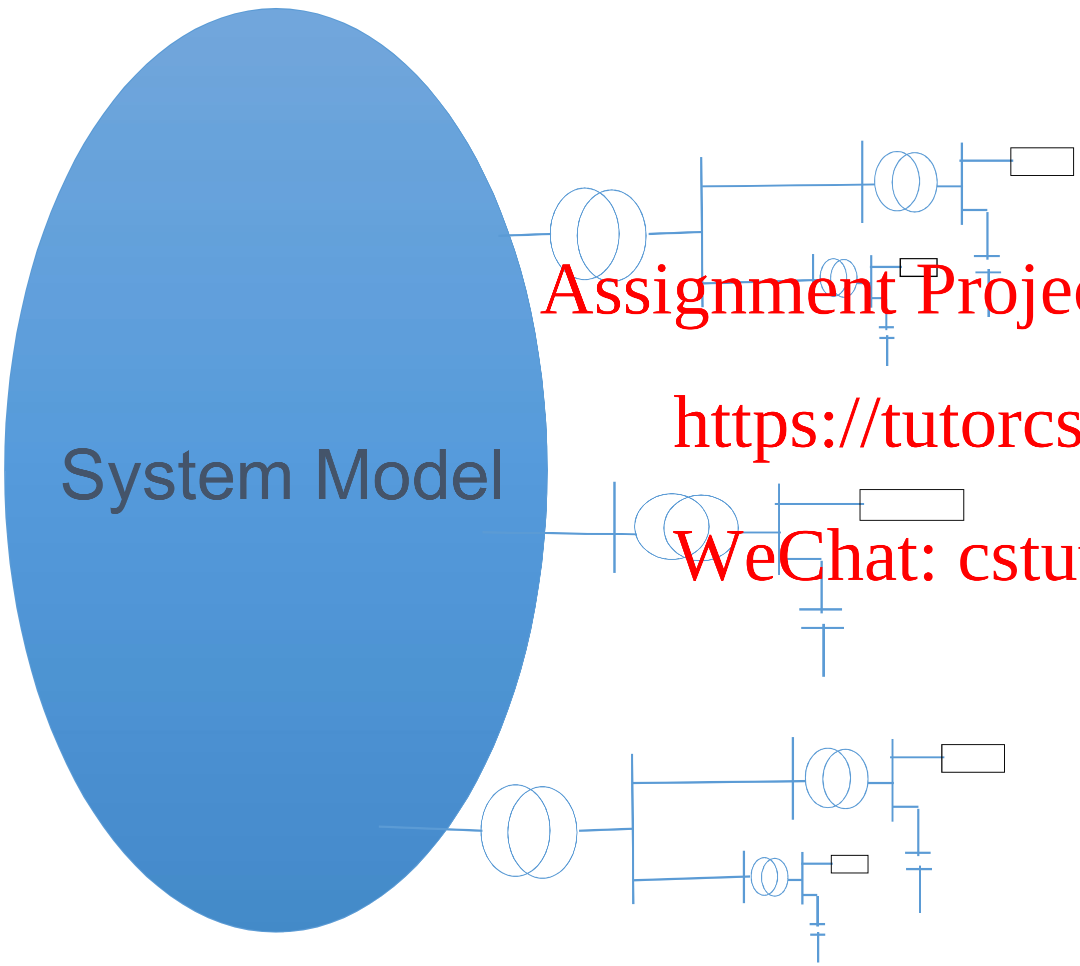
What is a load (from a power system modelling context):

- Portion of a power system not explicitly represented in a system model, but treated as if it were a single power consuming device connected to a bus in a system model.

- Load includes not only the connected load devices, but some or all of the following:
  - Substation step-down transformers
  - Subtransmission / distribution feeders
  - Shunt capacitors (for VAr control)
  - Voltage regulators
  - Customer wiring, transformers and capacitors

- Accurate load representation requires models that takes into account elements not represented in the system model.

Bus Loads, including feeders. Transformers, shunt capacitors and consumer loads



- LOAD COMPONENT is the aggregate equivalent of all devices of a similar type (e.g. water heater, air conditioner, fluorescent lighting etc)
- LOAD CLASS is a category of load, such as residential, commercial or industrial. For load modelling it is important to group loads into several classes, where each class has similar load compositions and characteristics.
- LOAD COMPOSITION: fractional composition of load by load components. This term maybe applied to bus load by load classes.
- LOAD CHARACTERISTICS: set of parameters, such as power factor, variation of P & Q with V, variation of P & Q with frequency etc., that characterise the behaviour of a specific load.

Power System Loads

Bulk power delivery point

Bus load = P+ jQ

Industrial Commercial Residential Agricultural …

Load class mix

Space heater Water heater Air Cond. Lighting Refrigeration

Load components

Power factor P(f,V) Q(f,V) Motor parameters

Individual components characteristics

Load Models:

- LOAD MODEL is a mathematical representation of the relationship between a bus voltage (magnitude & frequency) and the power (active & reactive)
- STATIC LOAD MODEL expresses active and reactive power at any instant of time as a function of voltage magnitude and frequency at same instant of time.
- DYNAMIC LOAD MODEL expresses active and reactive power at any instant of time as a function of voltage magnitude and frequency at past instants of time.

Static Load Models:

- CONSTANT IMPEDANCE LOAD MODEL: power varies with square of voltage magnitude.

$$P = P_0\left(\frac{V}{V_0}\right)^2 \qquad Q = Q_0\left(\frac{V}{V_0}\right)^2$$

- CONSTANT CURRENT LOAD MODEL: power varies with voltage magnitude.

$$P = P_0\left(\frac{V}{V_0}\right) \qquad Q = Q_0\left(\frac{V}{V_0}\right)$$

- CONSTANT POWER LOAD MODEL: power does not vary with changes in voltage magnitude.

$$P = P_0 \qquad Q = Q_0$$

- EXPONENTIAL LOAD MODEL: represents relationship between power & voltage as an exponential equation.
- POLYNOMIAL LOAD MODEL: represents relationship between power & voltage magnitude as polynomial equation.

Static Load Models - 1

Exponential (classical) load model

$$P = P_0 \left(\frac{V}{V_0} \right)^{n_p}$$

n_p corresponds to the slope dP/dV at V_0 of P=f(V) curve

$$Q = Q_0 \left(\frac{V}{V_0} \right)^{n_q}$$

n_q corresponds to the slope dQ/dV at V_0 of Q=g(V) curve

$n_p = n_q = 2$ - Constant impedance load

$n_p = n_q = 1$ - Constant current load

$n_p = n_q = 0$ - Constant power load

Generally:

n_p can have any value between 0 and 3

n_q can have any value between 0 and 7

Static Load Models - 2

Polynomial load models:

$$P = P_0[p_1\left(\frac{V}{V_0}\right)^2 + p_2\left(\frac{V}{V_0}\right) + p_3]$$

$$Q = Q_0[q_1\left(\frac{V}{V_0}\right)^2 + q_2\left(\frac{V}{V_0}\right) + q_3]$$

ZIP (constant impedance, constant current, constant power) load model

$$p_1 + p_2 + p_3 = 1$$

$$q_1 + q_2 + q_3 = 1$$

ZIP load model including frequency dependency $K_{pf} = 0 - 3; K_{qf} = -2 - 0$

$$P = P_0[p_1\left(\frac{V}{V_0}\right)^2 + p_2\left(\frac{V}{V_0}\right) + p_3][1 + K_{pf}(\frac{f - f_0}{f_0})]$$

$$Q = Q_0[q_1\left(\frac{V}{V_0}\right)^2 + q_2\left(\frac{V}{V_0}\right) + q_3][1 + K_{qf}(\frac{f - f_0}{f_0})]$$

Static Load Models - 3

$$P = P_0 \left(\frac{V}{V_0} \right)^{n_p} [1 + K_{pf} (\frac{f - f_0}{f_0})]$$

$$Q = Q_0 \left(\frac{V}{V_0} \right)^{n_q} [1 + K_{qf} (\frac{f - f_0}{f_0})]$$

Exponential load model including frequency dependency

Comprehensive static load models:

$$P = P_0 \{ p_1 \left(\frac{V}{V_0} \right)^2 + p_2 \left(\frac{V}{V_0} \right) + p_3 + p_4 \left(\frac{V}{V_0} \right)^{n_{p1}} [1 + K_{pf1} (\frac{f - f_0}{f_0})] + p_5 \left(\frac{V}{V_0} \right)^{n_{p2}} [1 + K_{pf2} (\frac{f - f_0}{f_0})] \}$$

$$Q = Q_0 \{ q_1 \left(\frac{V}{V_0} \right)^2 + q_2 \left(\frac{V}{V_0} \right) + q_3 + q_4 \left(\frac{V}{V_0} \right)^{n_{q1}} [1 + K_{qf1} (\frac{f - f_0}{f_0})] + q_5 \left(\frac{V}{V_0} \right)^{n_{q2}} [1 + K_{qf2} (\frac{f - f_0}{f_0})] \}$$

Need for improved load representation:

- If load representations produce overly-pessimistic results:
  - For planning studies, benefits of improved modelling will be deferring or avoiding system changes.
  - For operating studies, benefits will be increasing power transfer limits, with resulting economic benefits.
- If load representations produce overly-optimistic results:
  - For planning studies, benefits of improved modelling will be avoiding system inadequacies that may result in costly operating limitations.
  - For operating studies, benefit may be in preventing system emergencies resulting from overly-optimist operating limits
- Difficult to quantify benefits of improved load representation, but studies have been reported and impact can be significant .

Examples, using improved load representations

- Voltage stability study on Pacific Northwest System (USA):
  - When heating load of the residential part of the winter peak load was represented accurately a considerably higher transfer limit was achieved. This resulted in a saving in capital expenditure.
- However, an optimistic load model could push a system beyond actual limits and make them vulnerable to collapses.
  - For example, the Tokyo collapse of 1987 was partly due to underestimating the characteristics of reactive power compensation of air conditioning units.
- Common philosophy, in absence of accurate data on load characteristics, is to assume a pessimistic representation, to ensure a safety margin exists in operating limits.
  - However, what is believed to pessimistic may not be for all parts of the system or all operating scenarios.

First-swing Transient Stability Studies:

- System voltages are normally depressed during the first angular swing following a fault.
  - Large and rapid voltage excursions are seen during the initiating fault and slower voltage excursions during the first power swing.
  - Power consumed by loads during this period affects generation-load power imbalance, angular excursion and first swing stability.

- Consider, loads with a constant current characteristic, i.e. power consumption varies directly with magnitude of voltage.
  - If a constant impedance load model was used, power consumption varies with square of voltage and consequently would be lower than actual load during depressed voltage period.
  - For loads near accelerating generators this gives pessimistic results, since generation-load imbalance will be increased.
  - However, for loads remote from accelerating generators, this has an optimistic impact on the results.

Small-signal Stability Damping Studies:

- Inter-area modes of oscillation, involving multiple generators widely distributed over a power system, often result in significant variations in voltage and local frequency.
  - Load voltage and frequency characteristics have a significant effect on the damping of the oscillations.
  - Studies on damping of power-angle oscillations indicate response to voltage & frequency variations is important.

- Study for Western North America power system, showed that using a constant impedance load representation in small signal analysis tended to overestimate damping by 25% as compared with more accurate load representations.

Voltage Stability Analysis:

- Simple static load modelling is generally not appropriate for voltage stability analysis.
- Example: Use of simple load models failed to explain the voltage collapse seen in Sweden in 1983 (led to Blackout).
  - Load characteristics at low voltage (<0.8 pu) do not follow the characteristics traditionally used in stability studies.

- Voltage stability studies performed by Ontario Hydro (Canada) emphasised need for accurate dynamic load modelling.
  - Study of the impact of losing one line feeding Ottawa indicated a significant difference exists between studies performed with static and dynamic load models. Former led to wrong conclusions.

- Conclusion: no general rule for which load model to use. Utilities need to identify the load characteristics of a given system and use models appropriate for studies being performed.

Load Modelling Considerations:

- Consider dynamic performance studies related to:
  - First swing transient stability studies.
  - Small signal stability damping
  - Synchronizing power margins
  - Load/generation imbalance
  - Induction machine stability
  - Cold-load pickup
  - Voltage stability
  - Dynamic overvoltages
- Whether or not a load component should be modelled in detail depends on how much the component response affects the voltage and frequency excursions typical of that type of study.

Load Modelling: First swing transient stability

- 1st swing exhibits large and rapid voltage excursions during the initiating fault and slower voltage excursions during the 1st power angle swing, which lasts < 1 s.
- Load response to these voltage changes is important. Power consumed by the loads during this period affect the generation-load power imbalance and thereby affects the magnitude of the angular excursion and the first swing stability of the system.
- There is also a brief frequency excursion during the power-angle swing, so the frequency characteristics of loads close to accelerating or decelerating generators can be important.

Load Modelling: Small-Signal Stability Damping

- When studying damping of power-angle oscillation, typically in range 0.1 – 1.2 Hz, load response to sinusoidal variations in voltage and frequency is important.
- Frequency variations are greatest near the generators that have the greatest participation in the mode of oscillation.
- Voltage variations tend to be greatest at intermediate points between opposing groups of generators

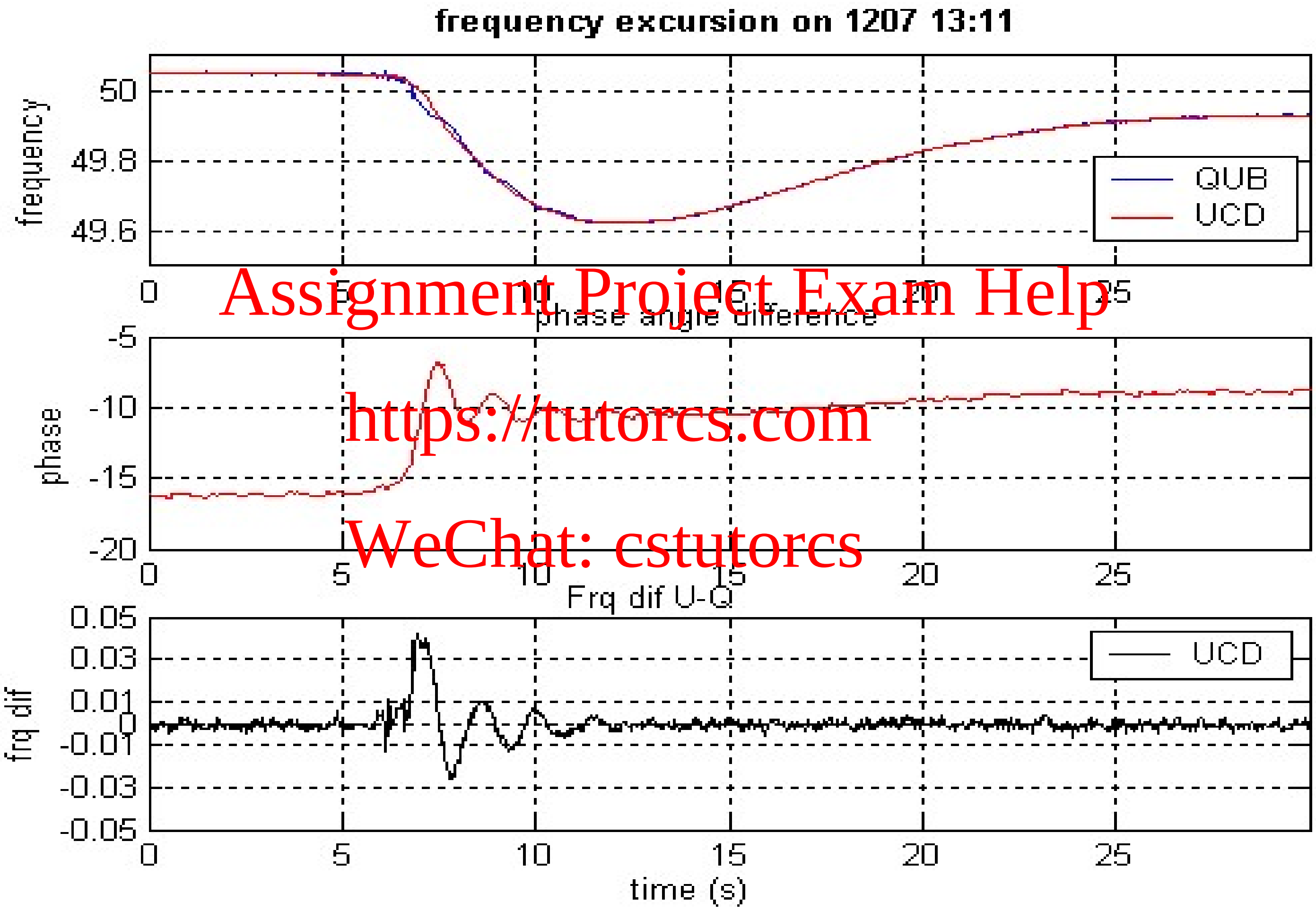
Load Modelling: Synchronising Power Margins

- Studies of synchronizing power margins require evaluation of periods from 1 minute to 20 minutes after a major disturbance.
- Hence long-term load voltage characteristics and the effect of tap-changing transformers are important when the angles across a power system approaches 90º.

Load Modelling: Voltage Stability

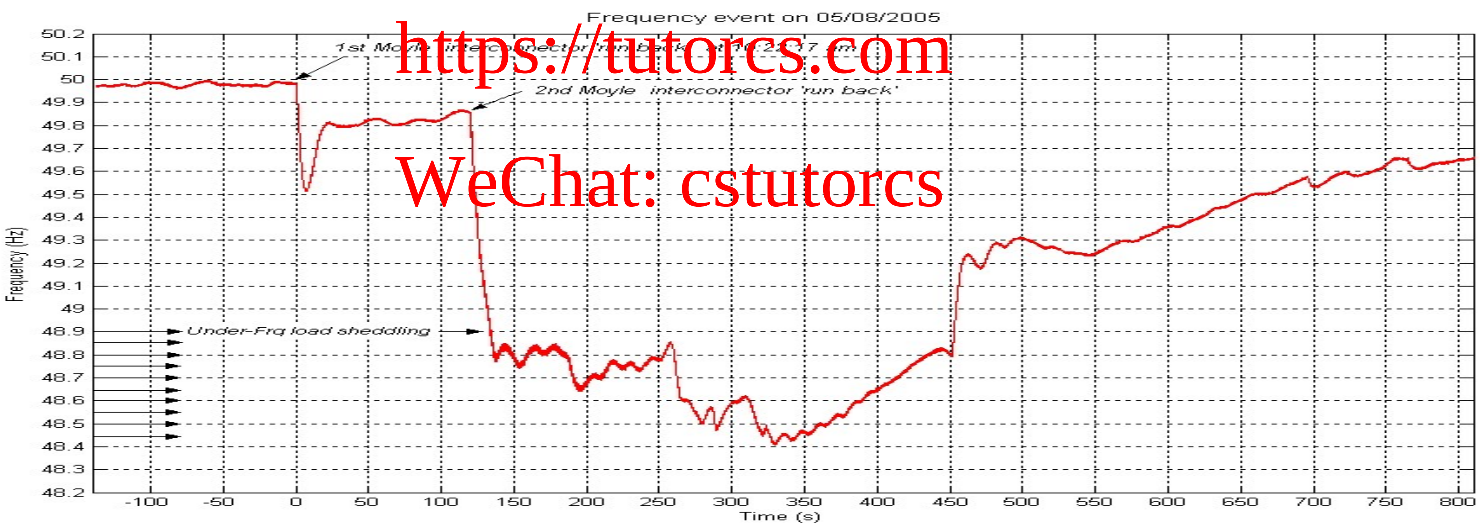
- Voltage stability is usually a longer term problem, and the load modelling requirements are similar to maintaining the synchronizing power margins to avoid instability.
- Characteristics of loads under abnormally low voltage conditions and the action of transformer tap changers or other voltage control devices must be accurately modelled.

Low frequency oscillations between Belfast and Dublin



Load Modelling: Generation-Load Imbalance

- Response of loads to frequency decay rates (0.1 – 4 Hz/s is important for generation-load imbalance studies.
- If rate of change of frequency is low, loads follow their long-term voltage and frequency characteristics.
- If rate of change of frequency is high, inertia and electrical time constants of motors affect the loads.



Major Disturbance on the All-Ireland network (5/8/2005)

Load Modelling: Induction motor stability

- In induction motor stability studies, issue is whether motor will re-accelerate or stall following the clearance of a fault.
- Motor and shaft load inertia, contactor hold-in characteristics and motor electrical parameters, such as the rotor circuit time constant are as important as the stiffness of the power system.

Cold Load Pickup

- In cold load pickup studies, almost all customer load devices are important.
- For example, thermostats may add load devices whilst the feeder is open, whilst protection devices might disconnect motors.
- Motor starting currents and inertia affect the current in the feeder when the power is restored.

Loads can be characterised as follows:

- Loads that exhibit “fast dynamic” electrical and mechanical characteristics, primary examples are the mechanical and electrical time constants of induction motors.
- Loads whose response to voltage excursions exhibit significant discontinuities, includes
  - Discharge lighting: constant current active power, reactive power α voltage raised to 4^{th} power, extinguish at 80% rated voltage.
  - Adjustable speed drives, shut down on low voltages (<80% rated V).
  - Motor contactors that open during faults and voltage swings removing motor from system. Motor overload protection that removes stalled motors from system.
- Loads whose response to voltage excursions does not exhibit significant discontinuities or time lags; small motors, incandescent lights, resistive loads
- Loads with slow dynamic characteristics: loads controlled by thermostats and manually controlled loads that change from constant resistance to constant power.

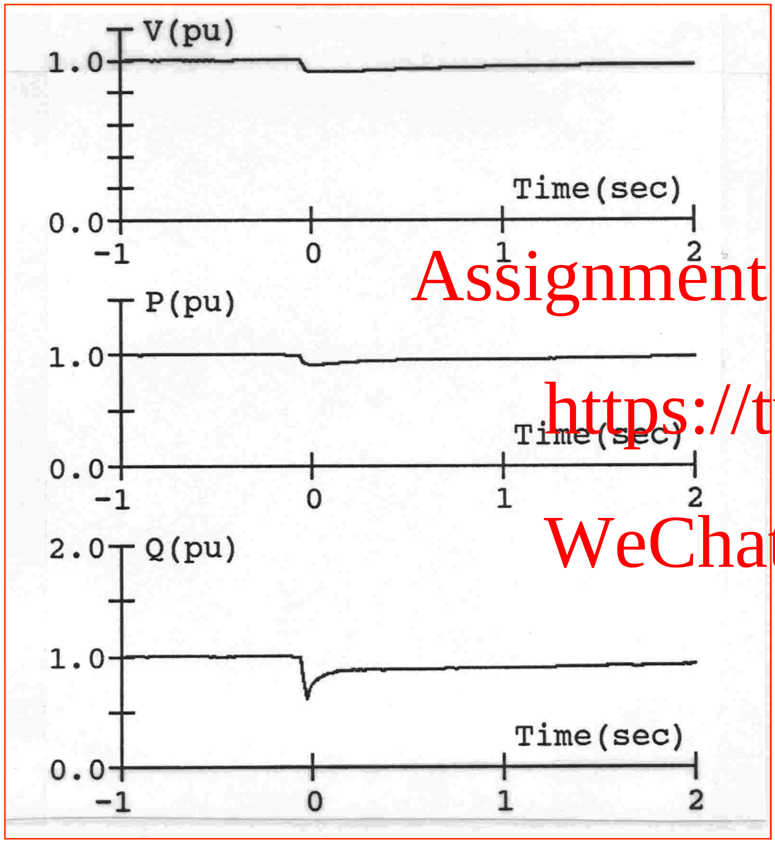
Individual Load Parameters

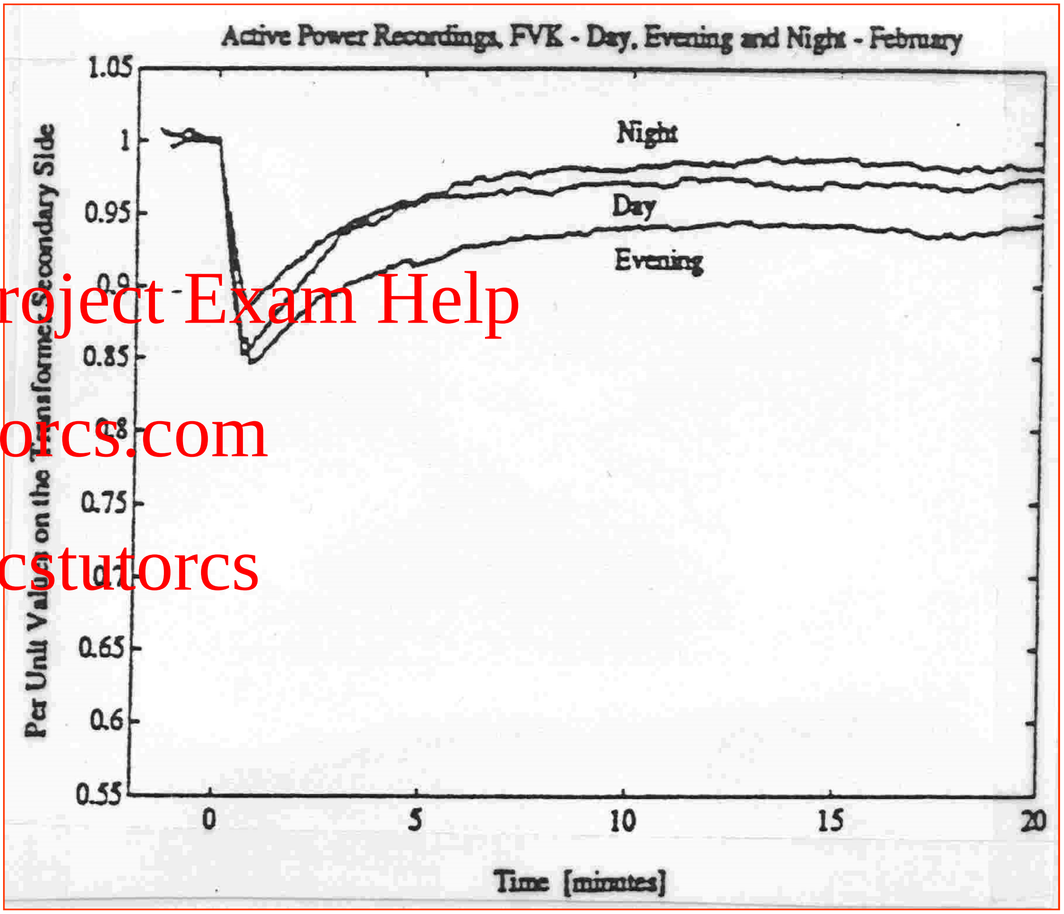
Component	Power factor	$\partial P/\partial V$	$\partial Q/\partial V$	$\partial P/\partial f$	$\partial Q/\partial f$
Air conditioner					
3-phase central	0.90	0.088	2.5	0.98	-1.3
1-phase central	0.96	0.202	2.3	0.90	-2.7
Window type	0.82	0.468	2.5	0.56	-2.8
Water heaters, Range top, oven, Deep fryer	1.0	2.0	0	0	0
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

Aggregate Load Parameters

Load class	Power factor	$\partial P/\partial V$	$\partial Q/\partial V$	$\partial P/\partial f$	$\partial Q/\partial f$
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

Measured Load Responses





Measured load responses of mixed commercial/domestic loads

Dynamic Load Models

- Responses of many composite loads to small changes in voltage and frequency is very fast and a new steady state is reached quickly - static load models are justified for such cases!
- Studies of inter-area oscillations, voltage stability and long term stability (or systems with large concentration of induction motors) require load dynamics to be modelled.

Contributors to Load Dynamics

- Induction motors - time response up to a few seconds
- Discharge lamps (mercury vapour, sodium vapour and fluorescent lamps) - extinguish at voltages of 0.7 p.u. – 0.8 p.u. and restart with 1 s to 2 s delay.
- Thermal and overcurrent relays
- Thermostatic control of loads (space heaters/coolers, water coolers, refrigerators)
- On Load Tap Changing transformers - control starts about 1 min after the disturbances and voltages are restored within 2 min - 3 min.

Generic Dynamic Load Models:

Model 1

$$pX_p = \frac{1}{T_p}(-X_p + P_s(V) - P_t(V))$$

$$P = X_p + P_t(V)$$

Model 2

$$pX_p = \frac{1}{T_p}(-X_p + P_s(V) - P_t(V))$$

$$P = X_p P_t(V)$$

Static and transient power characteristics can be conveniently defined as:

$$P_s(V) = P_0\left(\frac{V}{V_0}\right)^{n_{ps}}$$

$$P_t(V) = P_0\left(\frac{V}{V_0}\right)^{n_{pt}}$$

Similar equations apply for reactive power

$0 < n_{ps} < 3$ $\quad$ $0 < n_{qs} < 7$

$1.5 < n_{pt} < 2.5$ $\quad$ $4 < n_{qt} < 7$

Q & A

Thanks:

Any questions on Load Modelling?