Load Models in Power System Simulation

Geeven V Moodley

SAIEE LOAD RESEARCH CHAPTER (LRC) PRESENTATION

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Presentation Overview

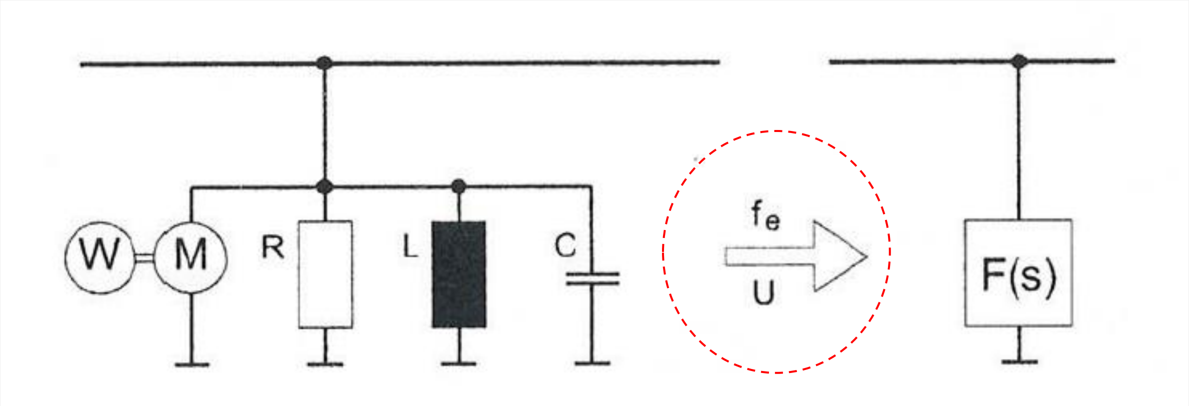
- Introduction
- General Load model representation in simulations
  - Voltage dependency of loads (Load Flow)
  - Short Circuit studies
  - Power Quality Studies
  - RMS Simulations
  - EMT Simulations

- Complex Load model
- MV Load model
- LV Load Model

- Deriving load model factors: System Parameter Identification

Nature of loads

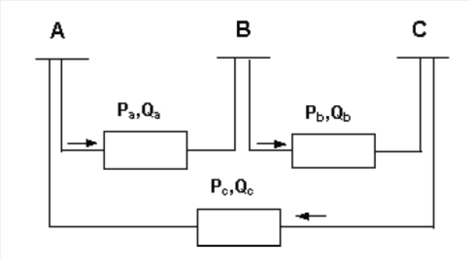
- In power systems, electrical load consists of various different types of electrical devices, from incandescent lamps and heaters to large arc furnaces and motors.
- It is often very difficult to identify the exact composition of static and dynamic loads in the network.
- The load composition can also vary depending on factors such as the season, time of day etc.
- Additionally, the term 'load' can be used for entire MV feeders in case of an HV system, or for LV feeders in the case of an MV system.

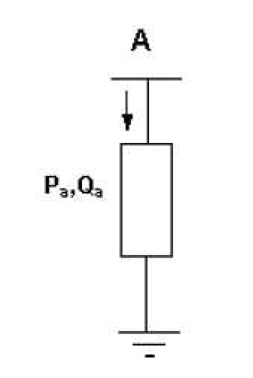


Load model representation in simulation

- Loads can be BALANCED or UNBALANCED
- Typically specify 2 parameters of P, Q, S, cosphi, I

- BALANCED
  - Assume that the load is shared equally between all phases
  - Delta, YN, 3Ph-E,
- UNBALANCED
  - 1 and 2 Ph loads
  - Specify parameters per phase
  - 2PH-E, 2PH-N, 1Ph-Ph, 1Ph-E, 1Ph-N





Load Flow: Voltage Dependency of Loads

- In reality, the power consumed by a load is a function of the supply voltage magnitude.
- Load flow calculations do not consider frequency dependency as the load flow assumes the frequency is fixed (50Hz)

- This has lead to the classical ZIP model development in order to represent the voltage dependency

Constant Z = Impedance I = Current P = Power

- Examples:
  - Z: kettle, geyser
  - I : arc furnace
  - P : motor drives (where constant torque is required)

Load Flow: Dependency of Loads

- Voltage dependency can be represented by

$$P_{cons} = P_{specified} \left(\frac{U_{supp}}{U_{nom}} \right)^{kP}$$

Load model type	Exponential coefficient
Constant power	0
Constant current	1
Constant impedance	2

Assume 10MW load with U_{supp}*=1.03*

- Constant P: $P_{cons} = 10 \left(\frac{1.03}{1.0} \right)^{0}$ = 10.0MW
- Constant I: $P_{cons} = 10 \left(\frac{1.03}{1.0} \right)^{1}$ = 10.3MW
- Constant Z: $P_{cons} = 10 \left(\frac{1.03}{1.0} \right)^{2}$ = 10.6MW

Load Flow: Voltage Dependency of Loads

- In reality the load 'seen' from a point in the network is a mix of these load types
- Also the reactive component of the load also has a voltage dependency factor(s).

$$P = P_0 \cdot \left[aP \cdot \left(\frac{|u|}{u_0} \right)^{e\_aP} + bP \cdot \left(\frac{|u|}{u_0} \right)^{e\_bP} + (1 - aP - bP) \cdot \left(\frac{|u|}{u_0} \right)^{e\_cP} \right]$$

$$Q = Q_0 \cdot \left[aQ \cdot \left(\frac{|u|}{u_0} \right)^{e\_aQ} + bQ \cdot \left(\frac{|u|}{u_0} \right)^{e\_bQ} + (1 - aQ - bQ) \cdot \left(\frac{|u|}{u_0} \right)^{e\_cQ} \right]$$

where aP, bP , cP , aQ, bQ and cQ are the proportional coefficients and e_aP, e_bP , e_cP , e_aQ, e_bQ and e_cQ are the exponents. u0 is the voltage input parameter and |u| is the absolute voltage where the load is connected.

- NOTE: The Q exponents can be significantly higher than 2 for loads with significant amount of induction machines e.g. extensive air conditioning

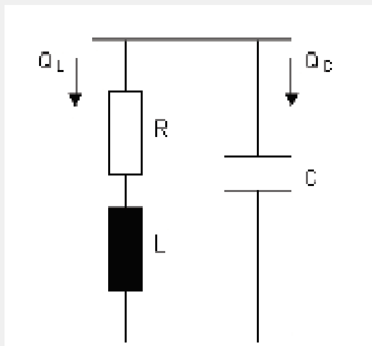
Short Circuit: Load models

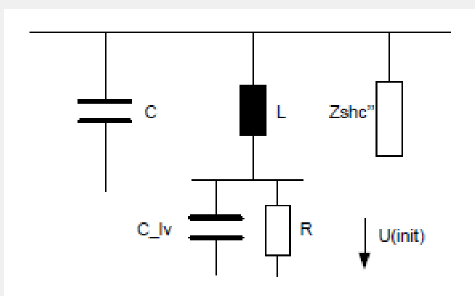
- Short-circuit calculations according to IEC 60909, VDE102/103 or ANSI C37 generally neglect loads and only consider motor contributions*.

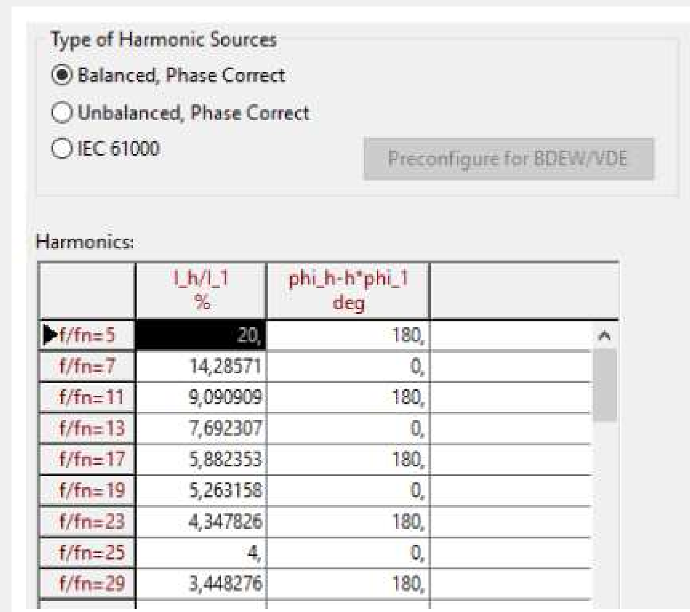
- * The IEC 60909 standard only calculates the sub-transient time phase. For calculating DC time constants, transient or steady state short-circuit currents, the rules defined in the short-circuit standards are applied

Power Quality: Harmonic Studies

- There are 2 load models typically used for harmonic studies
  - Impedance model
  - Current Source



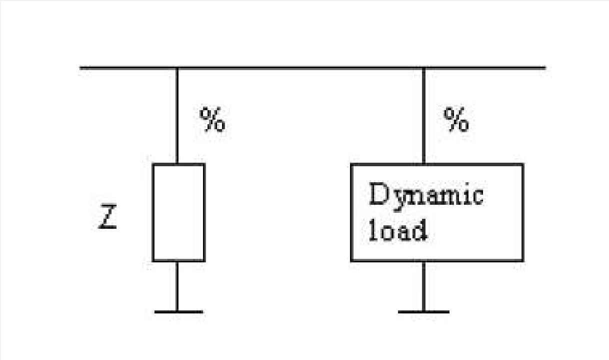




	I_h/I_1 %	phi_h-h*phi_1 deg
f/fn=5	20,	180,
f/fn=7	14,28571	0,
f/fn=11	9,090909	180,
f/fn=13	7,692307	0,
f/fn=17	5,882353	180,
f/fn=19	5,263158	0,
f/fn=23	4,347826	180,
f/fn=25	4,	0,
f/fn=29	3,448276	180,

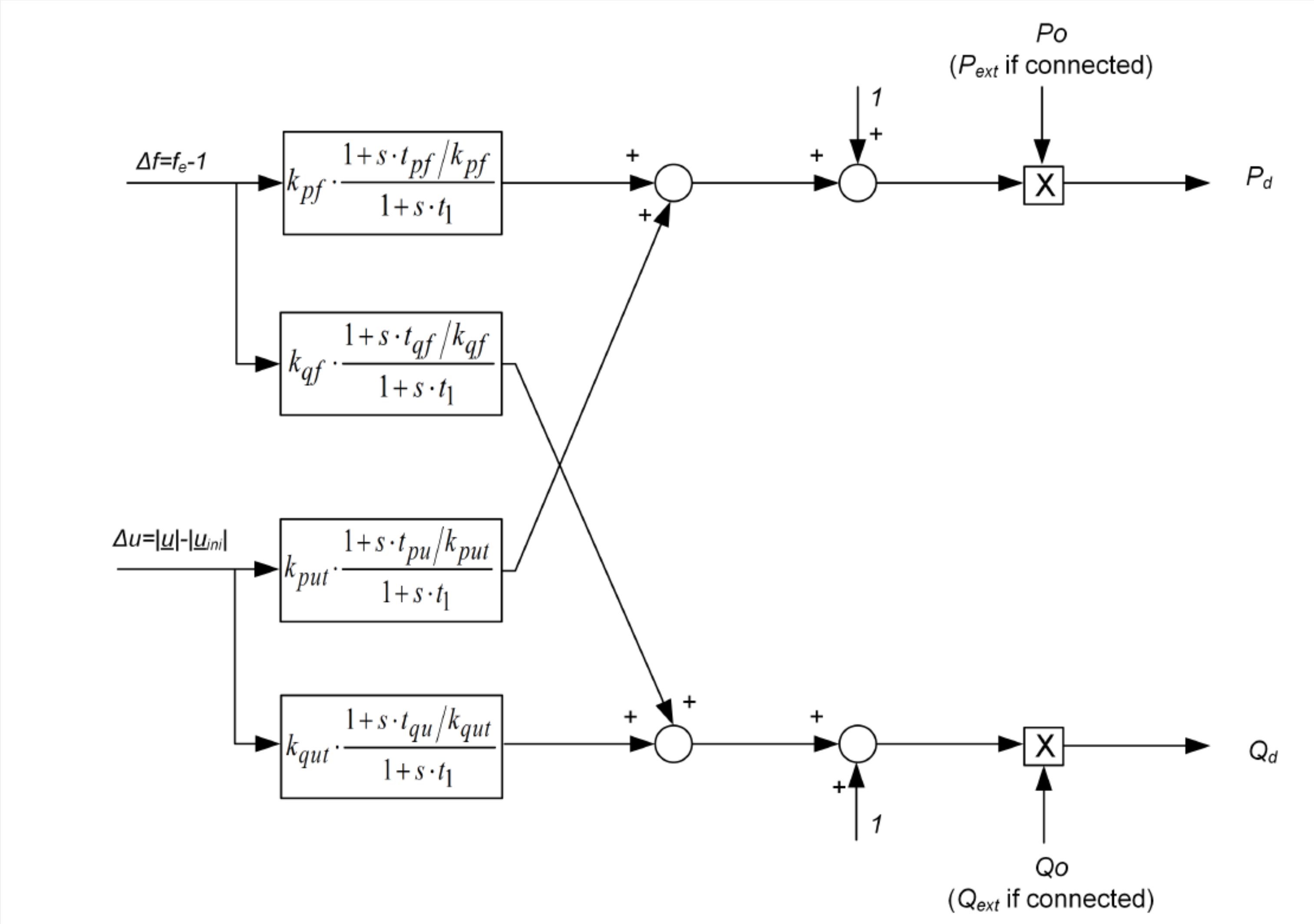
RMS Simulation

- Loads can be modelled as pure static, pure dynamic or a combination of both
- Static loads are ohmic, inductive or capacitive loads, and the dynamic load considers motor loads (especially induction motors).



- Dynamic loads also can consider frequency dependency hence the combination of voltage and frequency dependency must be considered

RMS Simulation: Linear voltage and linear frequency dependence model



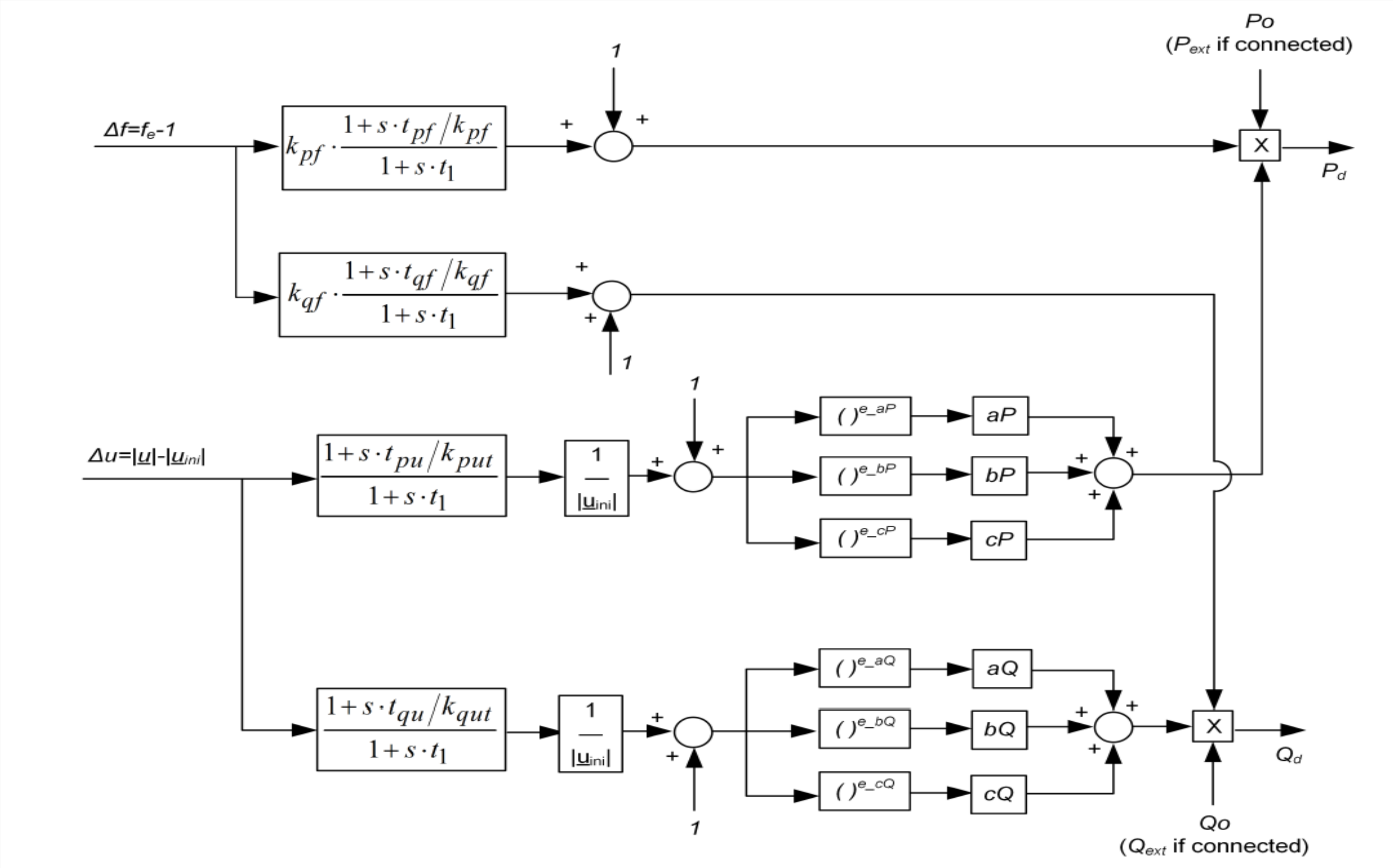
$$k_{pf}\cdot\frac{1+s\cdot t_{pf}/k_{pf}}{1+s\cdot t_1}$$

$$k_{qf}\cdot\frac{1+s\cdot t_{qf}/k_{qf}}{1+s\cdot t_1}$$

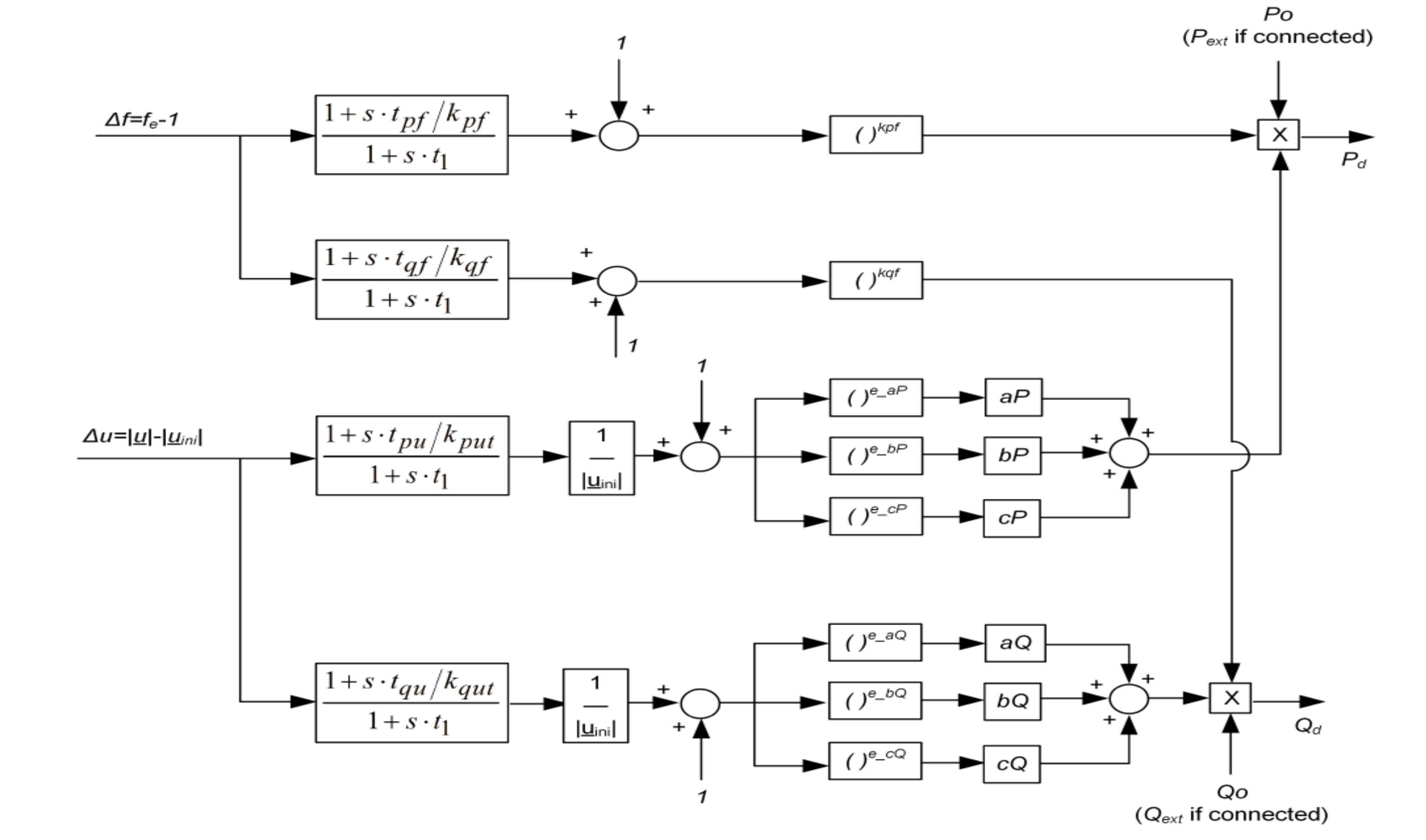
$$k_{put}\cdot\frac{1+s\cdot t_{pu}/k_{put}}{1+s\cdot t_1}$$

$$k_{qut}\cdot\frac{1+s\cdot t_{qu}/k_{qut}}{1+s\cdot t_1}$$

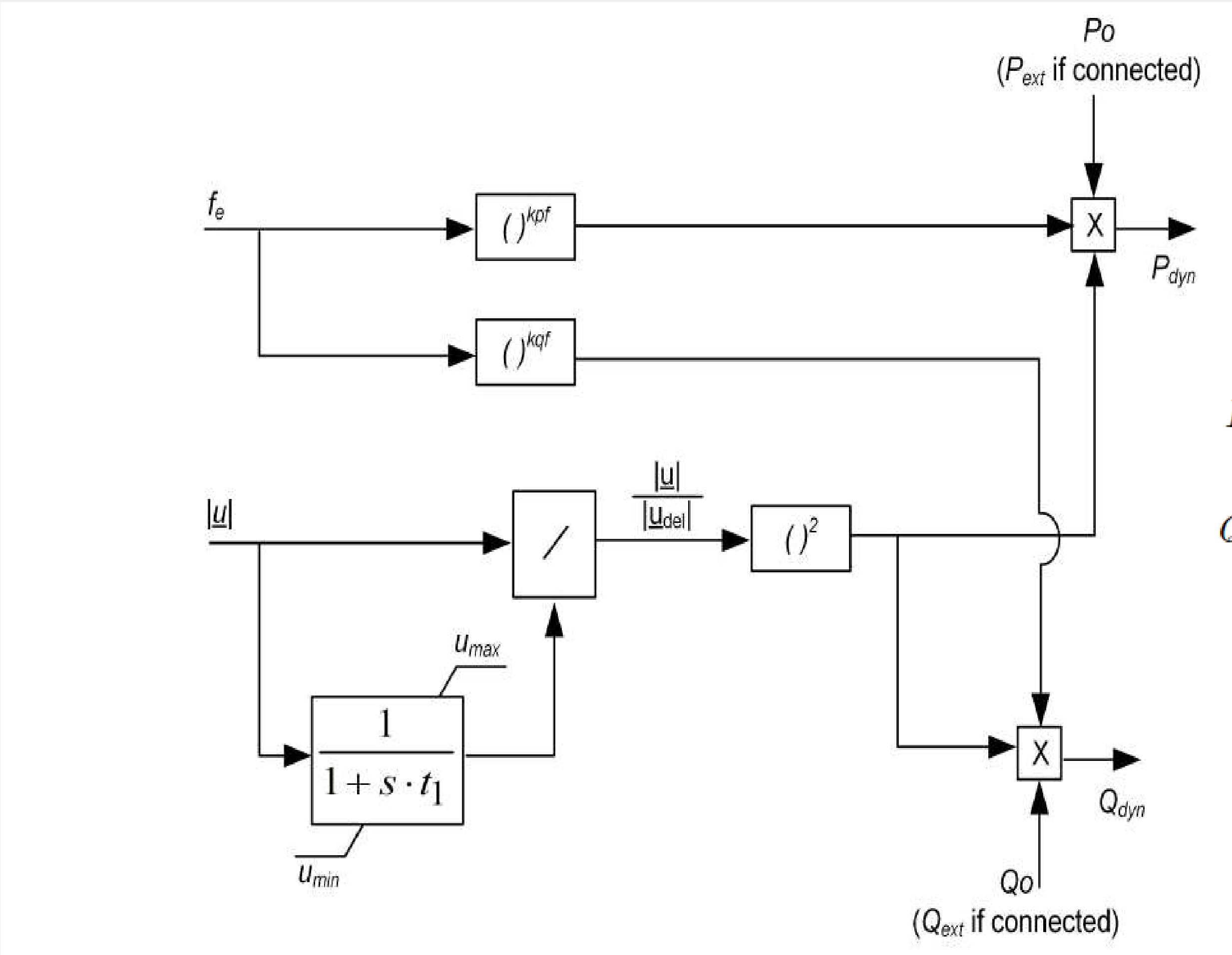
RMS Simulation: Nonlinear voltage and linear frequency dependence model



RMS Simulation: Nonlinear voltage and linear frequency dependence model



RMS Simulation: Nonlinear, regulated model



$$P_{dyn} = P_0 \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{del}|}\right)^2 \cdot \left(\frac{f_e}{1}\right)^{kpf}$$

$$Q_{dyn} = Q_0 \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{del}|}\right)^2 \cdot \left(\frac{f_e}{1}\right)^{kqf}$$

EMT Simulation

- Loads are typically modelled as passive loads
- Modelled as purely capacitive/ inductive or a combination of both (mix).

$$u_a = Rr \cdot i_{L\_a} + Lr \cdot \frac{di_{L\_a}}{dt}$$
$$u_b = Rs \cdot i_{L\_b} + Ls \cdot \frac{di_{L\_b}}{dt}$$
$$u_c = Rt \cdot i_{L\_c} + Lt \cdot \frac{di_{L\_c}}{dt}$$
$$i_a = i_{L\_a} + Cr \cdot \frac{du_a}{dt}$$
$$i_b = i_{L\_b} + Cs \cdot \frac{du_b}{dt}$$
$$i_c = i_{L\_c} + Ct \cdot \frac{du_c}{dt}$$

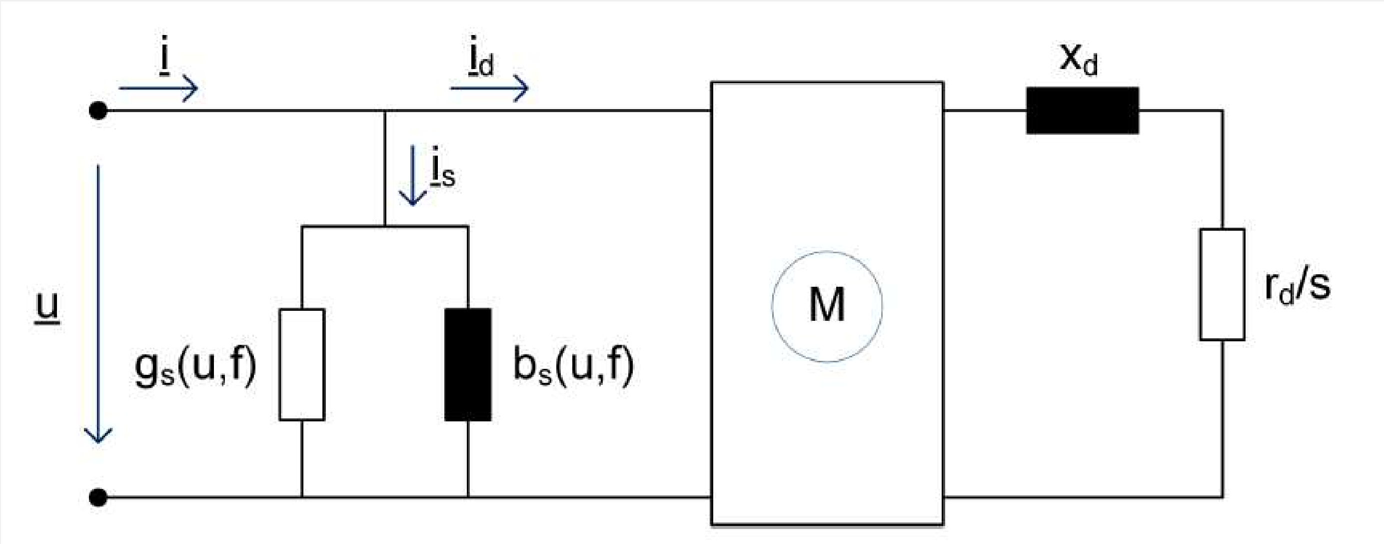
Y connected loads

$$u_a - u_b = Rr \cdot i_{L\_ab} + Lr \cdot \frac{di_{L\_ab}}{dt}$$
$$u_b - u_c = Rs \cdot i_{L\_bc} + Ls \cdot \frac{di_{L\_bc}}{dt}$$
$$u_c - u_a = Rt \cdot i_{L\_ca} + Lt \cdot \frac{di_{L\_ca}}{dt}$$
$$i_a = i_{L\_ab} + Cr \cdot \left(\frac{du_a}{dt} - \frac{du_b}{dt}\right) - \left(i_{L\_ca} + Ct \cdot \left(\frac{du_c}{dt} - \frac{du_a}{dt}\right)\right)$$
$$i_b = i_{L\_bc} + Cs \cdot \left(\frac{du_b}{dt} - \frac{du_c}{dt}\right) - \left(i_{L\_ab} + Cr \cdot \left(\frac{du_a}{dt} - \frac{du_b}{dt}\right)\right)$$
$$i_c = i_{L\_ca} + Ct \cdot \left(\frac{du_c}{dt} - \frac{du_a}{dt}\right) - \left(i_{L\_bc} + Cr \cdot \left(\frac{du_b}{dt} - \frac{du_c}{dt}\right)\right)$$

Delta connected loads

Complex Load Model

- It is often very difficult to identify the exact composition of static and dynamic loads in the network.
- This is particularly relevant to large industrial loads with a large portion of induction motors.
- ‘Complex load’ model can also be used with a static and dynamic portion.



Complex Load: Load Flow

- Static portion is represented by extended polynomial for voltage dependency.

$$p = p_0 \cdot k_p = p_0 \cdot \left(aP \cdot \left(\frac{u}{u_0}\right)^{e\_aP} + bP \cdot \left(\frac{u}{u_0}\right)^{e\_bP} + (1 - aP - bP) \cdot \left(\frac{u}{u_0}\right)^{e\_cP} \right)$$

$$q = q_0 \cdot k_q = q_0 \cdot \left(aQ \cdot \left(\frac{u}{u_0}\right)^{e\_aQ} + bQ \cdot \left(\frac{u}{u_0}\right)^{e\_bQ} + (1 - aQ - bQ) \cdot \left(\frac{u}{u_0}\right)^{e\_cQ} \right)$$

Load model type	Exponential coefficient
Constant power	0
Constant current	1
Constant impedance	2

- Dynamic portion is represented by simplified asynchronous machine model using impedance and normal operating slip

$$\underline{i}_d = \frac{\underline{u}}{\underline{z}_d} = \frac{\underline{u}}{\frac{r_d}{s_0/100} + \jmath \cdot x_d}$$

$$x_d = \frac{u_0^2}{p} \cdot \frac{100}{t_{m0}} \cdot \frac{s_0 \cdot s_{cr}}{s_0^2 + s_{cr}^2}$$

$$r_d = x_d \cdot \frac{s_{cr}}{100}$$

Complex Load: RMS Simulation

- Static portion is presented by

$$\underline{i}_s = \underline{u} \cdot (g_s \cdot k_p \cdot dP_f + j \cdot b_s \cdot k_q \cdot dQ_f) \cdot \frac{u_0^2}{u^2} \cdot k_{approx}$$

$$dP_f = 1 + kpf \cdot (f_e - 1)$$
$$dQ_f = 1 + kqf \cdot (f_e - 1)$$

Frequency dependency

$$P = k_{approx} \cdot P_{out}$$
$$Q = k_{approx} \cdot Q_{out}$$

$$k_{approx} = \begin{cases} 1 & u_{\min} < u < u_{\max} \\ \dfrac{2 \cdot |u|^2}{u_{\min}^2} & 0 < u < \dfrac{u_{\min}}{2} \\ k = 1 - 2 \cdot \left(\dfrac{|u| - u_{\min}}{u_{\min}}\right)^2 & \dfrac{u_{\min}}{2} < u < u_{\min} \\ k = 1 + (|u| - u_{\max})^2 & u > u_{\max} \end{cases}$$

Voltage Dependency

Complex Load: RMS Simulation

- Dynamic Portion

$$\underline{i}_d = \frac{\underline{\psi}_s - \underline{\psi}_r}{x_d}$$

$$\underline{\psi}_s = -\jmath \cdot \underline{u} / f_e$$

$$0 = -r_d \cdot \underline{i}_d + \jmath \cdot s \cdot \underline{\psi}_r - \frac{1}{2 \cdot \pi \cdot F_{nom}} \cdot \frac{d\,\underline{\psi}_r}{dt}$$

Stator flux

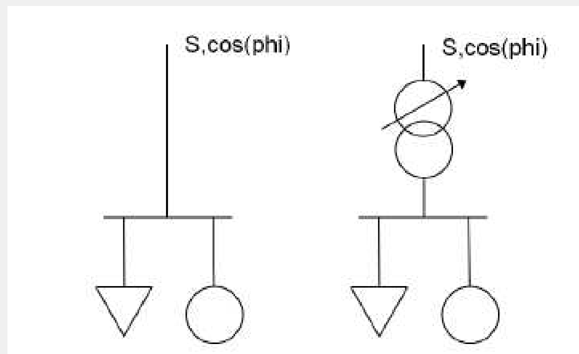
Rotor flux

$$s = f_e - speed$$

$$\frac{d\,speed}{dt} = \frac{xme - xmt}{T_j}$$

MV Load representation

- With increasing embedded generation in MV networks, the MV load model represents an aggregation of general loads and static generation in MV networks.



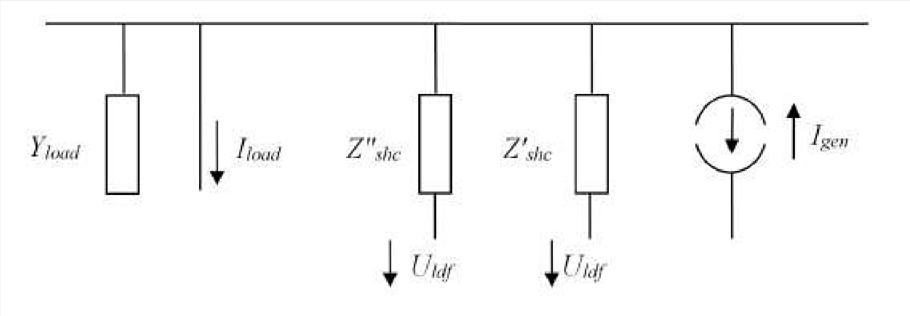
- For load flow studies the voltage dependency of the load portion is represented.

$$P = P_0 \left(aP + bP \cdot \left(\frac{v}{v_0} \right) + cP \cdot \left(\frac{v}{v_0} \right)^2 \right)$$

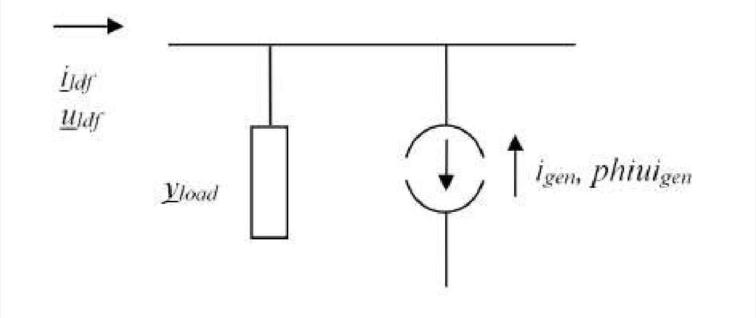
$$Q = Q_0 \left(aQ + bQ \cdot \left(\frac{v}{v_0} \right) + cQ \cdot \left(\frac{v}{v_0} \right)^2 \right)$$

MV Load Model

- For Short circuit studies, the current injection of the embedded generation must be taken into account (Complete Method only)



- RMS Simulation considers the load and current source



LV Load Models

- The focus of load flow calculations in low-voltage systems is usually to determine maximum branch currents as well as maximum voltage drop.
- In low-voltage systems the R/X ratio is considerably greater than 1. The voltage drop therefore depends mainly on the active power flow. Reactive power flow in low-voltage systems is of less interest.
- The modelling of loads, as for distribution systems, represents a major challenge. In addition to the time dependency, a **stochastic component** is introduced in low-voltage systems which is usually expressed in the form of a **coincidence factor**.
- This takes into consideration that for two connections it is highly unlikely that both will draw maximum load at the same time. With three connections this is even more unlikely. Therefore, the maximum load current depends on the number of connections supplied by a cable.

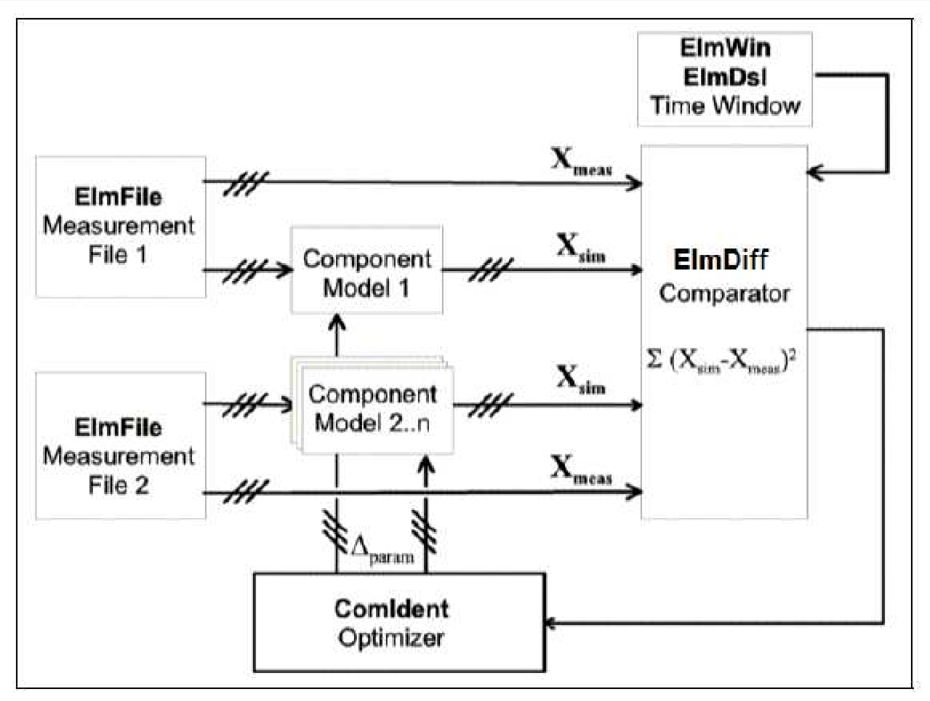
LV Load Models

- Voltage dependency of LV loads must be taken into account
- Co-incidence factor are dependent on the nature of the loads in an area, season, month of the year etc
- Short circuit current contributions are neglected by the standards (IEC, VDE)
- For harmonic analysis these loads are represented as purely inductive/capacitve/mix
- RMS studies these loads are considered as constant impedance
- EMT studies consider the loads as passive , which is inductive/capacitive

Deriving the coefficients / factors for load models

- System parameter Identification is a method of comparing measured results (P,Q,I and U) against simulated results, and adjusting the simulation parameters until a acceptable error /tolerance is achieved.
- Verification can be done using load flow or dynamic simulation

- Some commonly used optimization methods are;
  - Particle Swarm Optimisation
  - Nelder Mead
  - DIRECT (dividing rectangles)
  - BFGS
  - Legacy (Quasi-Newton)



Load Models: What is useful for simulation tools?

- The aim is to have a table of factors / exponents / coefficients that allow the simulation to accurately represent the South(ern) African network load behavior for both static and dynamic studies.

	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

IEEE Task Force on Load Representation for Dynamic Performance, IEEE Transactions on Power System, Vol 8, No 2, May 1993

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