Wind-Electric Icemaking Project: Analysis and Dynamometer Testing Volume II

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A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Work performed under Task No. WE805020

July 1998

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Volume II

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APPENDIX A: Mathematical Description of Steady State Model

MATHEMATICAL DESCRIPTION OF STEADY-STATE MODEL

Electrical diagram and designations used are shown in Chapter 3. Input parameters and basic equations are given below.

Input parameters

R_a - alternator stator phase resistance

L_s - alternator stator phase inductance

R_1, R_2 - motor stator and rotor resistances

L_1, L_2 - motor stator and rotor leakage inductances

L_m - mutual inductance between motor stator and rotor

R_c - core-losses resistance

p_{alt} - number of alternator pairs of poles

p_m - number of motor pairs of poles

f - alternator output frequency

s - motor slip

K - Alternator volt/hertz ratio

Basic equations

Electrical frequency in the system (rad/sec):

$$\omega_e(f) := 2 \cdot \pi \cdot f$$

Phase EMF induced in alternator stator (volt):

$$E_a(f) := K \cdot f$$

Alternator impedance (ohm):

$$Z_s(f) := R_a + j \cdot \omega_e(f) \cdot L_s$$

Motor stator impedance (ohm):

$$Z_1(f) := R_1 + j \cdot \omega_e(f) \cdot L_1$$

Motor rotor impedance (ohm):

$$Z_2(f, s) := \frac{R_2}{s} + j \cdot \omega_e(f) \cdot L_2$$

Motor shunt-branch impedance (ohm):

$$Z_{\phi}(f) := \frac{jR_c \cdot \omega_e(f) \cdot L_m}{R_c + j \cdot \omega_e(f) \cdot L}$$

Motor total impedance (ohm):

$$Z_m(f, s) := Z_1(f) + \frac{Z_{\phi}(f) \cdot Z_2(f, s)}{Z_{\phi}(f) + Z_2(f, s)}$$

Capacitor impedance (ohm):

$$Z_{c1}(f, C_1) := -j \cdot \frac{1}{\omega_e(f) \cdot C_1}$$

Total circuit impedance (ohm):

$$Z_{tot}(f, s, C_1) := Z_s(f) + Z_{c1}(f, C_1) + Z_m(f, s)$$

Current from alternator (amp):

$$I_a(f, s, C) := \frac{E_a(f)}{Z_{tot}(f, s, C)}$$

Alternator output voltage (volt):

$$V_{alt}(f, s, C) := E_a(f) - I_a(f, s, C) \cdot Z_s(f)$$

Motor input voltage (volt):

$$V_{mot}(f, s, C) := E_a(f) - I_a(f, s, C) \cdot (Z_s(f) + Z_{c1}(f, C))$$

Alternator output power (watt):

$$P_{alt}(f, s, C) := 3 \cdot \text{Re} \left(\overline{I_a(f, s, C)} \cdot V_{alt}(f, s, C) \right)$$

Alternator electromagnetic power (watt):

$$P_{alt.em}(f, s, C) := P_{alt}(f, s, C) + 3 \cdot \left(|I_a(f, s, C)| \right)^2 \cdot R_a$$

Alternator electromagnetic torque (Nm):

$$T_{alt}(f, s, C) := \frac{P_{alt.em}(f, s, C)}{\frac{\omega_e(f)}{P_{alt}}}$$

Motor electromagnetic power (Watt):

$$P_{m.em}(f, s, C) := (1 - s) \cdot \frac{2 \cdot \omega_e(f)}{P_m} \cdot T_m(f, s, C)$$

Motor electromagnetic torque (Nm):

$$T_m(f, s, C) := \frac{P_{alt}(f, s, C) - 3 \cdot \left(|I_a(f, s, C)| \right)^2 \cdot R_l}{\frac{\omega_e(f)}{P_m}}$$

Motor RPM:

$$n(f, s) := 30 \cdot f \cdot \frac{1 - s}{P_m}$$

Wind rotor shaft power as a function of wind speed V (m/sec) and alternator output frequency:

$$P_{rotor}(V, f) := \frac{1}{2} \cdot \rho \cdot A \cdot C_p(\lambda) \cdot V^3$$

where: ρ - air density (kg/m^3); A - swept area (m^2); $C_p(\lambda)$ - coefficient of performance as a function of tip speed ratio λ ; V - wind speed (m/sec).

Motor load torque can be represented as any function of slip $F(s)$:

$$T_{load}(s) := F(s)$$

APPENDIX B: Mathematical Description of Dynamic Model

MATHEMATICAL DESCRIPTION OF DYNAMIC MODEL

1. System of base values

Motor rated parameters:

Current - I_{rated} , Voltage - U_{rated} , Frequency - f_{rated}

Number of alternator pairs of poles - p_{alt}

Number of motor pairs of poles - p_{mot}

<p>Base voltage (volt):</p> $U_{\text{base}} := U_{\text{rated}} \sqrt{2}$ <p>Base current (amp):</p> $I_{\text{base}} := I_{\text{rated}} \sqrt{2}$ <p>Base power (watt):</p> $P_{\text{base}} := \frac{3}{2} U_{\text{base}} I_{\text{base}}$ <p>Base frequency:</p> $f_{\text{base}} := f_{\text{rate}}$ <p>Base electrical angular speed (rad/sec):</p> $\omega_{\text{base}} := 2 \cdot \pi \cdot f_{\text{base}}$ <p>Base angular mechanical speed (rad/sec):</p> $\Omega_{\text{base}} := \frac{\omega_{\text{base}}}{p_{\text{alt}}}$ <p>Base RPM:</p> $N_{\text{base}} := \frac{60 \cdot f_{\text{base}}}{p_{\text{alt}}}$ <p>Base time:</p> $t_{\text{base}} := \frac{1}{\omega_{\text{base}}}$	<p>Base resistance (ohm):</p> $Z_{\text{base}} := \frac{U_{\text{base}}}{I_{\text{base}}}$ <p>Base inductance (henry):</p> $L_{\text{base}} := \frac{Z_{\text{base}}}{\omega_{\text{base}}}$ <p>Base capacitance (farad):</p> $C_{\text{base}} := \frac{1}{\omega_{\text{base}} \cdot Z_{\text{base}}}$ <p>Base torque (Nm):</p> $T_{\text{base}} := \frac{P_{\text{base}}}{\Omega_{\text{base}}}$ <p>Base moment of inertia:</p> $J_{\text{base}} := \frac{p_{\text{alt}} T_{\text{base}}}{\omega_{\text{base}}^2}$ <p>Base charge:</p> $Q_{\text{base}} := I_{\text{base}} \cdot t_{\text{base}}$
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2. Input parameters

Parameters in p.u.

Alternator	Motor
<p>Resistance:</p> $R_{alt} := \frac{R_{alt}(\text{ohm})}{Z_{base}}$	<p>Stator resistance:</p> $R_{1.mot} := \frac{R_{1.mot}(\text{ohm})}{Z_{base}}$
<p>Leakage inductance:</p> $L_{\sigma.alt} := \frac{L_{\sigma.alt}(\text{henry})}{L_{base}}$	<p>Rotor resistance:</p> $R_{2.mot} := \frac{R_{2.mot}(\text{ohm})}{Z_{base}}$
<p>Direct-axis synchronous inductance:</p> $L_{md} := \frac{2}{3} \cdot \frac{L_{ad}(\text{henry})}{L_{base}}$	<p>Stator leakage inductance:</p> $L_{\sigma 1.mot} := \frac{L_{\sigma 1.mot}(\text{henry})}{L_{base}}$
<p>Quadrature-axis synchronous inductance:</p> $L_{mq} := \frac{2}{3} \cdot \frac{L_{aq}(\text{henry})}{L_{base}}$	<p>Rotor leakage inductance:</p> $L_{\sigma 2.mot} := \frac{L_{\sigma 2.mot}(\text{henry})}{L_{base}}$
<p>Alternator moment of inertia:</p> $J_{alt} := \frac{J_{alt}(\text{kg} \cdot \text{m}^2)}{J_{base}}$	<p>Motor mutual inductance:</p> $L_m := \frac{L_m(\text{henry})}{L_{base}}$
<p>Driving device moment of inertia:</p> $J_{dr} := \frac{J_{dr}(\text{kg} \cdot \text{m}^2)}{J_{base}}$	<p>Core-loss resistance:</p> $R_c := \frac{R_c(\text{ohm})}{Z_{base}}$
<p>Alternator volt/hertz ratio:</p> $K := \frac{K \left(\frac{\text{volt}}{\text{Hz}} \right)}{U_{base}} \cdot \sqrt{2} \cdot f_{bas}$	<p>Motor moment of inertia:</p> $J_{mot} := \frac{J_{mot}(\text{kg} \cdot \text{m}^2)}{J_{base}}$
<p>Capacitance:</p> $C := \frac{C(\text{farad})}{C_{base}}$	<p>Load moment of inertia:</p> $J_{load} := \frac{J_{load}(\text{kg} \cdot \text{m}^2)}{J_{base}}$

3. Initial conditions

Variable	Designation (p.u.)
Motor initial rotor angle:	$\gamma_{\text{mot}0}$
Motor initial angular mechanical speed:	$\Omega_{\text{mot}0}$
Alternator initial rotor angle:	$\gamma_{\text{alt}0}$
Alternator initial angular mechanical speed (in p.u. this value is equal to alternator output frequency):	$\Omega_{\text{alt}0}$
Charge through capacitor of phase "A":	Q_{A0}
Charge through capacitor of phase "B":	Q_{B0}
Charge through capacitor of phase "C":	Q_{C0}
Alternator phase "A" initial current:	I_{A0}
Alternator phase "B" initial current:	I_{B0}
Alternator phase "C" initial current:	I_{C0}
Motor rotor phase "a" initial current:	I_{a0}
Motor rotor phase "b" initial current:	I_{b0}
Motor rotor phase "c" initial current:	I_{c0}

4. Basic equations (in p.u.) for alternator

Average inductance:

$$L_{\text{alt.av}} := \frac{L_{\text{md}} + L_{\text{m}}}{2}$$

Amplitude of inductance variable component (in salient-pole alternators only):

$$L_{\text{alt.var}} := \frac{L_{\text{md}} - L_{\text{m}}}{2}$$

A,B,C-phase inductances and their time derivatives ($p=d/dt$):

$$\begin{aligned} L_{A.\text{alt}} &:= L_{\text{alt.av}} + L_{\text{alt.var}} \cos(2 \cdot \gamma_{\text{alt}}) + L_{\sigma.\text{al}} & pL_{A.\text{alt}} &:= -2 \cdot \Omega_{\text{alt}} L_{\text{alt.var}} \sin(2 \cdot \gamma_{\text{alt}}) \\ L_{B.\text{alt}} &:= L_{\text{alt.av}} + L_{\text{alt.var}} \cos\left(2 \cdot \gamma_{\text{alt}} + \frac{2}{3} \pi\right) + L_{\sigma.\text{al}} & pL_{B.\text{alt}} &:= -2 \cdot \Omega_{\text{alt}} L_{\text{alt.var}} \sin\left(2 \cdot \gamma_{\text{alt}} + \frac{2}{3} \pi\right) \\ L_{C.\text{alt}} &:= L_{\text{alt.av}} + L_{\text{alt.var}} \cos\left(2 \cdot \gamma_{\text{alt}} + \frac{4}{3} \pi\right) + L_{\sigma.\text{al}} & pL_{C.\text{alt}} &:= -2 \cdot \Omega_{\text{alt}} L_{\text{alt.var}} \sin\left(2 \cdot \gamma_{\text{alt}} + \frac{4}{3} \pi\right) \end{aligned}$$

Mutual inductances between stator phases and their time derivatives:

$$\begin{aligned} L_{AB.alt} &:= -\frac{L_{alt.av}}{2} + L_{alt.var} \cos\left(2 \cdot \gamma_{alt} + \frac{4}{3} \cdot \pi\right) & pL_{AB.alt} &:= -2 \cdot \Omega_{alt} L_{alt.var} \sin\left(2 \cdot \gamma_{alt} + \frac{4}{3} \cdot \pi\right) \\ L_{AC.alt} &:= -\frac{L_{alt.av}}{2} + L_{alt.var} \cos\left(2 \cdot \gamma_{alt} + \frac{2}{3} \cdot \pi\right) & pL_{AC.alt} &:= -2 \cdot \Omega_{alt} L_{alt.var} \sin\left(2 \cdot \gamma_{alt} + \frac{2}{3} \cdot \pi\right) \\ L_{BC.alt} &:= -\frac{L_{alt.av}}{2} + L_{alt.var} \cos\left(2 \cdot \gamma_{alt}\right) & pL_{BC.alt} &:= -2 \cdot \Omega_{alt} L_{alt.var} \sin\left(2 \cdot \gamma_{alt}\right) \end{aligned}$$

Time derivatives of mutual inductances between stator and PM rotor:

$$\begin{aligned} pL_{Af} &:= -\frac{3}{2} \cdot 2 \cdot \Omega_{alt} L_{md} \sin\left(2 \cdot \gamma_{alt}\right) \\ pL_{Bf} &:= -\frac{3}{2} \cdot 2 \cdot \Omega_{alt} L_{md} \sin\left(2 \cdot \gamma_{alt} + \frac{4}{3} \cdot \pi\right) \\ pL_{Cf} &:= -\frac{3}{2} \cdot 2 \cdot \Omega_{alt} L_{md} \sin\left(2 \cdot \gamma_{alt} + \frac{2}{3} \cdot \pi\right) \end{aligned}$$

E.M.F. induced in stator phases:

$$\begin{aligned} E_A &:= K \cdot \Omega_{alt} \sin\left(\gamma_{alt}\right) \\ E_B &:= K \cdot \Omega_{alt} \sin\left(\gamma_{alt} + \frac{4}{3} \cdot \pi\right) \\ E_C &:= K \cdot \Omega_{alt} \sin\left(\gamma_{alt} + \frac{2}{3} \cdot \pi\right) \end{aligned}$$

5. Basic equations (in p.u.) for motor

Stator inductances:

$$\begin{aligned} L_{A.mot} &:= L_m + L_{\sigma 1.mo} \\ L_{B.mot} &:= L_m + L_{\sigma 1.mo} \\ L_{C.mot} &:= L_m + L_{\sigma 1.mo} \end{aligned}$$

Stator mutual inductances:

$$\begin{aligned} L_{AB.mot} &:= -\frac{L}{2} \\ L_{AC.mot} &:= -\frac{L}{2} \\ L_{BC.mot} &:= -\frac{L}{2} \end{aligned}$$

Rotor inductances:

$$\begin{aligned} L_{a.mot} &:= L_m + L_{\sigma 2.mo} \\ L_{b.mot} &:= L_m + L_{\sigma 2.mo} \\ L_{c.mot} &:= L_m + L_{\sigma 2.mo} \end{aligned}$$

Rotor mutual inductances:

$$\begin{aligned} L_{ab.mot} &:= -\frac{L}{2} \\ L_{ac.mot} &:= -\frac{L}{2} \\ L_{bc.mot} &:= -\frac{L}{2} \end{aligned}$$

Mutual inductances between stator and rotor windings and their time derivatives:

$$L_{Aa} := L_m \cos(\gamma_{\text{mot}})$$

$$L_{Bb} := L_m \cos(\gamma_{\text{mot}})$$

$$L_{Cc} := L_m \cos(\gamma_{\text{mot}})$$

$$pL_{Aa} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin(\gamma_{\text{mot}})$$

$$pL_{Bb} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin(\gamma_{\text{mot}})$$

$$pL_{Cc} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin(\gamma_{\text{mot}})$$

$$L_{Ab} := L_m \cos\left(\gamma_{\text{mot}} + \frac{2}{3} \cdot \pi\right)$$

$$L_{Bc} := L_m \cos\left(\gamma_{\text{mot}} + \frac{2}{3} \cdot \pi\right)$$

$$L_{Ca} := L_m \cos\left(\gamma_{\text{mot}} + \frac{2}{3} \cdot \pi\right)$$

$$pL_{Ab} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{2}{3} \cdot \pi\right)$$

$$pL_{Bc} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{2}{3} \cdot \pi\right)$$

$$pL_{Ca} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{2}{3} \cdot \pi\right)$$

$$L_{Ac} := L_m \cos\left(\gamma_{\text{mot}} + \frac{4}{3} \cdot \pi\right)$$

$$L_{Ba} := L_m \cos\left(\gamma_{\text{mot}} + \frac{4}{3} \cdot \pi\right)$$

$$L_{Cb} := L_m \cos\left(\gamma_{\text{mot}} + \frac{4}{3} \cdot \pi\right)$$

$$pL_{Ac} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{4}{3} \cdot \pi\right)$$

$$pL_{Ba} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{4}{3} \cdot \pi\right)$$

$$pL_{Cb} := -\frac{p_{\text{mot}}}{p_{\text{alt}}} \cdot \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{4}{3} \cdot \pi\right)$$

6. Matrices

Matrix of inductances:

$$L := \begin{bmatrix} L_{A.\text{alt}} + L_{A.\text{mot}} & L_{AB.\text{alt}} + L_{AB.\text{mot}} & L_{AC.\text{alt}} + L_{AC.\text{mot}} & L_{Aa} & L_{Ab} & L_{Ac} \\ L_{AB.\text{alt}} + L_{AB.\text{mot}} & L_{B.\text{alt}} + L_{B.\text{mot}} & L_{BC.\text{alt}} + L_{BC.\text{mot}} & L_{Ba} & L_{Bb} & L_{Bc} \\ L_{AC.\text{alt}} + L_{AC.\text{mot}} & L_{BC.\text{alt}} + L_{BC.\text{mot}} & L_{C.\text{alt}} + L_{C.\text{mot}} & L_{Ca} & L_{Cb} & L_{Cc} \\ L_{Aa} & L_{Ba} & L_{Ca} & L_{a.\text{mot}} & L_{ab.\text{mot}} & L_{ac.\text{mot}} \\ L_{Ab} & L_{Bb} & L_{Cb} & L_{ab.\text{mot}} & L_{b.\text{mot}} & L_{bc.\text{mot}} \\ L_{Ac} & L_{Bc} & L_{Cc} & L_{ac.\text{mot}} & L_{bc.\text{mot}} & L_{c.\text{mot}} \end{bmatrix}$$

Matrix of inductances time derivatives:

$$pL := \begin{bmatrix} R_{alt} + R_{1.mot} + pL_{A.alt} & pL_{AB.alt} & pL_{AC.alt} & pL_{Aa} & pL_{Ab} & pL_{Ac} \\ pL_{AB.alt} & R_{alt} + R_{1.mot} + pL_{B.alt} & pL_{BC.alt} & pL_{Ba} & pL_{Bb} & pL_{Bc} \\ pL_{AC.alt} & pL_{BC.alt} & R_{alt} + R_{1.mot} + pL_{C.alt} & pL_{Ca} & pL_{Cb} & pL_{Cc} \\ pL_{Aa} & pL_{Ba} & pL_{Ca} & R_{2.mot} & 0 & 0 \\ pL_{Ab} & pL_{Bb} & pL_{Cb} & 0 & R_{2.mot} & 0 \\ pL_{Ac} & pL_{Bc} & pL_{Cc} & 0 & 0 & R_{2.mot} \end{bmatrix}$$

Matrix of voltages:

$$U := \left(E_A - \frac{1}{C} \cdot Q_A \quad E_B - \frac{1}{C} \cdot Q_B \quad E_C - \frac{1}{C} \cdot Q_C \quad 0 \quad 0 \quad 0 \right)$$

Matrixes A and B:

$$A := L^{-1}$$

$$B := L^{-1} \cdot p$$

Matrixes C and D:

$$C := (I_A \ I_B \ I_C \ A_0 \ A_1 \ A_2 \ A_3 \ A_4 \ A_5)$$

$$D := \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & B_{0,0} & B_{0,1} & B_{0,2} & B_{0,3} & B_{0,4} & B_{0,5} \\ 0 & 0 & 0 & B_{1,0} & B_{1,1} & B_{1,2} & B_{1,3} & B_{1,4} & B_{1,5} \\ 0 & 0 & 0 & B_{2,0} & B_{2,1} & B_{2,2} & B_{2,3} & B_{2,4} & B_{2,5} \\ 0 & 0 & 0 & B_{3,0} & B_{3,1} & B_{3,2} & B_{3,3} & B_{3,4} & B_{3,5} \\ 0 & 0 & 0 & B_{4,0} & B_{4,1} & B_{4,2} & B_{4,3} & B_{4,4} & B_{4,5} \\ 0 & 0 & 0 & B_{5,0} & B_{5,1} & B_{5,2} & B_{5,3} & B_{5,4} & B_{5,5} \end{bmatrix}$$

Matrix of currents and charges through capacitors:

$$X := (Q_A \ Q_B \ Q_C \ I_A \ I_B \ I_C \ I_a \ I_b \ I_c)$$

Matrix of currents and charges time derivatives ($p=d/dt$):

$$pX := (pQ_A \ pQ_B \ pQ_C \ pI_A \ pI_B \ pI_C \ pI_a \ pI_b \ pI_c)$$

Matrix G:

$$G := C - D \cdot X$$

7. Voltages, powers and electromagnetic torques:

Motor input phase voltages:

$$\begin{aligned}U_{A.mot} &:= E_A - (R_{alt} + pL_{A.alt})I_A - pL_{AB.alt}I_B - pL_{AC.alt}I_C - L_{A.alt}F_3 - L_{AB.alt}F_4 - L_{AC.alt}F_5 - \frac{Q_A}{C} \\U_{B.mot} &:= E_B - pL_{AB.alt}I_A - (R_{alt} + pL_{B.alt})I_B - pL_{BC.alt}I_C - L_{AB.alt}F_3 - L_{B.alt}F_4 - L_{BC.alt}F_5 - \frac{Q_B}{C} \\U_{C.mot} &:= E_C - pL_{AC.alt}I_A - pL_{BC.alt}I_B - (R_{alt} + pL_{C.alt})I_C - L_{AC.alt}F_3 - L_{BC.alt}F_4 - L_{C.alt}F_5 - \frac{Q_C}{C}\end{aligned}$$

Input power to motor (alternator output power):

$$P_1 := \frac{2}{3} (U_{A.mot}I_A + U_{B.mot}I_B + U_{C.mot}I_C)$$

Electrical losses in alternator stator:

$$P_{el.alt} := \frac{2}{3} R_{alt} (I_A^2 + I_B^2 + I_C^2)$$

Electrical losses in motor stator:

$$P_{el.mot} := \frac{2}{3} R_{l.mot} (I_A^2 + I_B^2 + I_C^2)$$

Alternator electromagnetic torque:

$$T_{em.alt} := \frac{P_1 + P_{el.al}}{\Omega_{alt}}$$

Motor electromagnetic torque:

$$T_{em.mot} := \frac{P_{mot}}{P_{alt}} \cdot \frac{P_1 - P_{el.mo}}{\Omega_{mot}}$$

8. Alternator driving torque

a) Wind rotor

Parameters: r - radius, A - swept area, J_{rotor} - moment of inertia, ρ - air density

$V(t)$ - wind speed as a function of time

Tip-speed ratio as a function of time:

$$\lambda(t) := \frac{r \Omega_{alt} \Omega_{base}}{V(t)}$$

Wind rotor coefficient of performance as a function of time in polynomial form:

$$C_p(t) := \sum_{i=0}^N K_i \lambda(t)^i$$

Wind rotor torque as a function of time:

$$T_{\text{rotor}}(t) := \frac{\frac{1}{2} \rho \cdot \text{Area} \cdot C_p(t) \cdot V(t)^3}{\Omega_{\text{alt}} P_{\text{base}}}$$

b) Driving motor

Parameters: $J_{\text{dr.mot}}$ - moment of inertia of driving motor

Driving motor torque referred to alternator shaft as a function of alternator speed and frequency of driving motor input voltage:

$$T_{\text{dr.mot}}(f, \Omega_{\text{alt}}) := -k_1(f) \cdot \Omega_{\text{alt}} + k_2(f)$$

Coefficients $k_1(f)$ and $k_2(f)$ are changed with the frequency of driving motor input voltage.

9. Motor load torque

J_{load} - load moment of inertia

Friction component of motor load torque:

$$T_{\text{friction}}(\Omega_{\text{mot}}) := H \cdot \Omega_{\text{mo}}$$

where H - constant coefficient

$T_{\text{load,average}}$ - constant component of motor load torque

Oscillating component of motor load torque as a function of time and motor speed:

$$T_{\text{oscillating}}(\Omega_{\text{mot}}, t) := \Delta T \cdot \cos(F(\Omega_{\text{mot}}) \cdot t)$$

where ΔT is an amplitude, and $F(\Omega_{\text{mot}})$ is a frequency of load oscillating component as a function of motor speed.

So the motor load torque:

$$T_{\text{load}}(\Omega_{\text{mot}}, t) := T_{\text{friction}}(\Omega_{\text{mot}}) + T_{\text{load,average}} + T_{\text{oscillating}}(\Omega_{\text{mot}}, t)$$

10. System of differential equations:

Alternator equations of motion ($p=d/dt$):

$$p\gamma_{alt} := \Omega_{al}$$

a) In case of wind rotor:

$$p\Omega_{alt} := \frac{T_{rotor}(t) - T_{em.al}}{J_{alt} + J_{rotor}}$$

b) In case of driving motor:

$$p\Omega_{alt} := \frac{T_{dr.mot}(f, \Omega_{alt}) - T_{em.al}}{J_{alt} + J_{dr.mot}}$$

Motor equations of motion:

$$p\gamma_{mot} := \frac{p_{mot}}{p_{alt}} \cdot \Omega_{mo}$$

$$p\Omega_{mot} := \frac{T_{em.mot} - T_{load}(\Omega_{mot}, t)}{J_{mot} + J_{load}}$$

System of differential equations of electrical equilibrium in vector form:

$$pX := C - D \cdot X$$

The vector of solutions in p.u. can be obtained by the joint numerical integration of equations of motion and equations of electrical equilibrium. In order to get all solutions in absolute units it is necessary to multiply every variable to corresponding a base value.

APPENDIX C: Bench-Scale Test Machinery Specifications

VARIABLE FREQUENCY DRIVE

Machine Type	Transistor Inverter
Manufacturer	Toshiba
Model No.	VF10P-2020B0
Number of Phases	Three
Rated kVA	2 kva
Nominal Input Line Voltage	230 vac
Frequency Range	6 to 60 hz
Rated Output Current	7 amps
Control System	Sinusoidal wave PWM control
Voltage/Frequency Ratio	Variable

DRIVE MOTOR

Machine Type	AC Induction Machine
Manufacturer	Baldor Electric Company
Model No.	A36B05-107
Frame	182TC 623M
Number of Phases	Three
Number of Poles	Four
Rated Power	3 hp
Rated Line-to-Line Voltage	230 vac
Rated Frequency	60 hz
Rated Stator Current	8.6 amps
Rated Speed	1725 rpm
Insulation	Class B

Permanent Magnet Alternator

Machine Type	Permanent Magnet Alternator
Manufacturer	World Power Technologies, Inc.
Model No.	Whisper 600HV
Number of Phases	Three
Number of Poles	10
Winding Configuration	Y-connected, 12 leads
Rated Power	600 watts
Rated Line-to-Line Voltage	280 vac
Rated Speed	1000 rpm
Rated Frequency	83.3 hz
Rated Current	2.2 amps

LOAD MOTOR

Machine Type	AC Induction Machine
Manufacturer	<i>for</i> Hampden Engineering Co.
Model No.	IM-100
Number of Phases	Three
Number of Poles	Four
Rotor Type	Squirrel-Cage
Stator Type	Wound, Y-connected
Rated Power	1/3 hp (250 watts)
Rated Line-to-Line Voltage	208 vac
Rated Frequency	60 hz
Rated Stator Current	1.7 amps
Synchronous Speed	1800 rpm
Insulation	Class B
Stator Circuit Protection	2.5 amp, 3-pole, thermal circuit breaker

DYNAMOMETER

Machine Type	DC Machine
Number of Poles	Two
Rated Power	1/3 hp (motoring); 333 watt (generating)
Rated Speed	1800 rpm
Rated Armature Voltage	125 vdc
Rated Armature Current	2.4 amps
Rated Field Voltage	125 vdc
Rated Field Current	0.5 amps
Insulation	Class F
Armature Circuit Protection	4.1 amp, 3-pole, thermal circuit breaker
Field Circuit Protection	1 amp slow-blow fuse

**APPENDIX D: Detailed Results for Tests 1 and 2
(Machine Parameter Determinations)**

Test 1a. No-Load Test for Load Motor

In this test the motor shaft was not connected to anything. The relationship between line-to-line voltage and line current is shown in the graph below. The slip was 0.002 for all cases (i.e., 1796 to 1797 rpm).

Test 1b. Locked-Rotor Test for Load Motor

In this test the load motor shaft was "locked" by the dynamometer. The relationship between line-to-line voltage and line current is shown in the figure below. The slip was 1.00 for all cases. Rated voltage was not applied because the high currents would trip the motor circuit breaker.

Test 1c. Leakage Induction Test for Load Motor

In this test the rotor was removed from the load motor. A voltage was applied line-to-line on the stator. The frequency was constant at 60 Hz. The voltage-current data from these tests are summarized in the following graph.

The leakage inductance was calculated from the following equation (note: this is actually twice the leakage inductance for a single phase since the windings are connected in wye and there is no lead at the neutral point):

$$L_1 := \frac{\sqrt{\frac{V^2}{I} - R_1^2}}{2 \cdot \pi \cdot f}$$

where V and I are shown in the figure above, R_1 is twice the stator phase resistance, and f is the frequency (60 Hz).

Test 1d. Stator Resistance Test for Load Motor

This was a very simple test in which an ohmmeter was used to measure the resistance across stator leads of the load motor. Again, the measured value was double the phase value because of the wye configuration.

Test 2a. Open-Circuit Test for Alternator

In this test the leads from the alternator stator were left open-circuited. The alternator was driven at three speeds which produced the following frequencies: 30, 60, and 90 Hz. The data from this test are shown in the figure below as square symbols. A line representing 5.0 Volt/Hz is also shown on this graph.

Test 2b. Resistive Load Test for Alternator

In this test the alternator was connected to a resistive load bank. The resistances used were: 99, 333, 400, 500, 667, 1000, and 2000 ohm. The alternator was run at three different frequencies (i.e., 46, 75, and 103 Hz). The data are summarized in the following graph.

Using these data and the following equation, the alternator inductances were calculated:

$$L_1 := \frac{\sqrt{\frac{E_a^2}{I} - (R_{load} + R_a)^2}}{2 \cdot \pi \cdot f}$$

where I is the measured line current, E_a is the alternator induced voltage, R_{load} is the load bank resistance, R_a is the alternator stator resistance, and f is the frequency. The resulting inductances are plotted in the following graph. A constant inductance value of 0.18 henry was used in the numerical models since the current would always be between 0.8 and 1.2 amps when the alternator was connected to the induction motor.

Test 2c. Stator Resistance Test for Alternator

This was a very simple test in which an ohmmeter was used to measure the resistance across stator leads of the alternator.

APPENDIX E: Detailed Results for Test 3 (Steady-State Line-Connected Induction Motor)

Test 3. Induction Motor Steady-State Operation

The following tables give the results for the line-connected (60 Hz) steady-state operation of the induction (load) motor. The motor was operated at three voltages: 60, 104, and 209.5 VAC. There were no capacitors used in any of these tests. The torque data is the most unreliable of all the data for a couple reasons. First, the friction losses in the system can account for substantial differences between the measured torque and the electromagnetic torque generated by the induction motor. Second, the torque generated by this equipment is generally much smaller than the load cell is capable of measuring. The full-scale torque for the load cell is 6.8 Nm and the torques measured for these tests are usually much smaller than that.

Applied Voltage = 60 VAC

Slip	Current (Amps)	Power (Watts)
0.031	0.429	35
0.076	0.75	64
0.114	0.95	83
0.157	1.079	95
0.197	1.23	109
0.267	1.429	123
0.326	1.7	132
0.426	1.83	139
0.564	2	144
0.709	2.1	146
0.754	2.2	147
1	2.3	150

Slip	Torque (Nm)
0.032	0.13
0.076	0.20
0.151	0.26
0.246	0.28
0.264	0.27
0.354	0.27
0.536	0.24
0.726	0.21
1.000	0.26

Applied Voltage = 104 VAC

Slip	Current (Amps)	Power (Watts)
0.009	0.6	38.4
0.039	0.652	120
0.091	1.06	177
0.111	1.455	233
0.137	1.69	258
0.171	1.869	288
0.214	2.173	329
0.264	2.46	366
0.333	2.8	407
0.414	3.2	429
1	4.1	490

Slip	Torque (Nm)
0.009	0.13
0.023	0.22
0.066	0.79
0.094	0.91
0.112	0.95
0.131	0.97
0.158	1.01
0.199	1.08
0.259	1.15
0.310	1.19
0.367	1.16
1.000	0.85

Applied Voltage = 209.5 VAC

Slip	Current (Amps)	Power (Watts)
0.003	1.35	91
0.011	1.361	167
0.041	1.7	400
0.056	1.93	580
0.083	2.38	790

Slip	Torque (Nm)
0.003	0.16
0.270	1.28
0.040	1.77
0.054	2.35
0.067	2.80
0.070	2.94
0.077	3.08

APPENDIX F: Detailed Results for Test 4 (Dynamic Line-Connected Induction Motor)

LINE CONNECTED MOTOR START-UP TEST

RPM = $60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$

Nm = newton·m

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Line-to-line voltage 106 volt

Test data are stored in the **line-04.dat** file in **NOLOAD** directory.

Data matrix: $M := \text{READPRN}(\text{line_04})$

Number of points: $N := \text{rows}(M) \cdot 0.95$ $N = 1.71 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec}$ $T_{\max} = 2.848 \cdot \text{sec}$

$i := 0..N-1$

Time: $t_i := M_{i,0} \cdot \text{sec}$ $R_1 := 5.8 \cdot \text{ohm}$ $p_m := 2$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp}$ $I_{B_i} := M_{i,2} \cdot \text{amp}$ $I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt}$ $U_{BC_i} := M_{i,5} \cdot \text{volt}$ $U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm}$ Instantaneous power to motor: $P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM}$ Alternator output frequency: $f_i := 60 \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := 72 \cdot \mu\text{F}$ Voltages across capacitor: $U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

LINE CONNECTED MOTOR START-UP TEST

RPM = $60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$

Nm = newton·m

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10-Power

11-Frequency

Line-to-line voltage 106 volt

Higher inertia

Test data are stored in the line-03.dat file in NOLOAD directory.

Data matrix: $M := \text{READPRN}(\text{line_03})$ Number of points: $N := \text{rows}(M) \cdot 0.95$ $N = 2.28 \cdot 10^3$ Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec}$ $T_{\max} = 3.798 \cdot \text{sec}$ $i := 0..N-1$ Time: $t_i := M_{i,0} \cdot \text{sec}$ $R_1 := 5.8 \cdot \text{ohm}$ $p_m := 2$ Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp}$ $I_{B_i} := M_{i,2} \cdot \text{amp}$ $I_{C_i} := M_{i,3} \cdot \text{amp}$ Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt}$ $U_{BC_i} := M_{i,5} \cdot \text{volt}$ $U_{CA_i} := M_{i,6} \cdot \text{volt}$ Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm}$ Instantaneous power to motor: $P_i := M_{i,9} \cdot \text{watt}$ Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM}$ Alternator output frequency: $f_i := 60 \cdot \text{Hz}$ Capacitance: $\text{Cap}_i := 72 \cdot \mu\text{F}$ Voltages across capacitor: $U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$ Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

LINE CONNECTED MOTOR START-UP TEST

RPM $\equiv 60\cdot\text{Hz}\cdot\text{sec}\cdot\text{min}^{-1}$ Nm $\equiv\text{newton}\cdot\text{m}$

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Line-to-line voltage 79 volt

Test data are stored in the line-01.dat file in NOLOAD directory.

Data matrix: $M := \text{READPRN}(\text{line_01})$ Number of points: $N := \text{rows}(M) \cdot 0.95$ $N = 2.28 \cdot 10^3$ Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec}$ $T_{\max} = 3.798 \cdot \text{sec}$ $i := 0..N - 1$ Time: $t_i := M_{i,0} \cdot \text{sec}$ $R_1 := 5.8 \cdot \text{ohm}$ $p_m := 2$ Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp}$ $I_{B_i} := M_{i,2} \cdot \text{amp}$ $I_{C_i} := M_{i,3} \cdot \text{amp}$ Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt}$ $U_{BC_i} := M_{i,5} \cdot \text{volt}$ $U_{CA_i} := M_{i,6} \cdot \text{volt}$ Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm}$ Instantaneous power to motor: $P_i := M_{i,9} \cdot \text{watt}$ Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM}$ Alternator output frequency: $f_i := 60 \cdot \text{Hz}$ Capacitance: $\text{Cap}_i := 72 \cdot \mu\text{F}$ Voltages across capacitor: $U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$ Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

**APPENDIX G: Detailed Results for Test 5 (Steady-State Alternator /
Induction Motor System)**

Locked-Rotor Test			
Current (Amps)			
Freq	Model	Test	Error
22	1.20	1.25	-4.00962
25	1.31	1.35	-3.04606
34	1.55	1.61	-3.48259
44	1.74	1.81	-3.60111
RMS Error =		3.551477	
Voltage			
Freq	Model	Test	Error
22	19.8	22.9	-13.6245
25	22.1	25.8	-14.1667
34	28.7	33.2	-13.5301
44	35.8	41.2	-13.0437
RMS Error =		13.59708

APPENDIX H: Detailed Results for Test 6 (Dynamic Alternator / Induction Motor System)

1. MOTOR NO LOAD START-UP TEST (35 Hz)

(capacitor was in the circuit during whole test)

RPM = $60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$ INPUT CHANNEL MAP
 Nm = newton·m
 1-Time
 2-IA
 3-IB
 4-IC
 5-VAB
 6-VBC
 7-VCA
 8-Torque
 9-Speed
 10 -Power
 11-Frequency

Test data are stored in the **nl35hz.dat** file in **NOLOAD** directory.

Data matrix: $M := \text{READPRN}(\text{nl35hz})$

Number of points: $N := \text{rows}(M) \cdot 0.95 \quad N = 2.28 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec} \quad T_{\max} = 3.798 \cdot \text{sec}$

$i := 0..N - 1$

Time: $t_i := M_{i,0} \cdot \text{sec} \quad R_l := 5.8 \cdot \text{ohm} \quad p_m := 2 \quad R_a := 36 \cdot \text{ohm} \quad p_{\text{alt}} := 5$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp} \quad I_{B_i} := M_{i,2} \cdot \text{amp} \quad I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt} \quad U_{BC_i} := M_{i,5} \cdot \text{volt} \quad U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm} \quad \text{Instantaneous power to motor: } P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM} \quad \text{Alternator output frequency: } f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := 72 \cdot \mu\text{F} \quad \text{Voltages across capacitor: } U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_l \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

Alternator torque: $T_{\text{alt}_i} := \frac{P_i + R_a \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_{\text{alt}}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

1. MOTOR NO LOAD START-UP TEST (45 Hz)

(capacitor was in the circuit during whole test)

RPM = 60 · Hz · sec · min⁻¹ INPUT CHANNEL MAP
 Nm = newton · m 1-Time
 2-IA
 3-IB
 4-IC
 5-VAB
 6-VBC
 7-VCA
 8-Torque
 9-Speed
 10 -Power
 11-Frequency

Test data are stored in the nl45hz.dat file in NOLOAD directory.

Data matrix: $M := \text{READPRN}(\text{nl45hz})$

Number of points: $N := \text{rows}(M) \cdot 0.95$ $N = 2.28 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec}$ $T_{\max} = 3.798 \cdot \text{sec}$

$i := 0..N - 1$

Time: $t_i := M_{i,0} \cdot \text{sec}$ $R_1 := 5.8 \cdot \text{ohm}$ $p_m := 2$ $R_a := 36 \cdot \text{ohm}$ $p_{\text{alt}} := 5$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp}$ $I_{B_i} := M_{i,2} \cdot \text{amp}$ $I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt}$ $U_{BC_i} := M_{i,5} \cdot \text{volt}$ $U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm}$ Instantaneous power to motor: $P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM}$ Alternator output frequency: $f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := 72 \cdot \mu\text{F}$ Voltages across capacitor: $U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

Alternator torque: $T_{\text{alt}_i} := \frac{P_i + R_a \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_{\text{alt}}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

1. MOTOR NO LOAD START-UP TEST (55 Hz.)

(capacitor was in the circuit during whole test)

$$\text{RPM} = 60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$$

$$\text{Nm} = \text{newton} \cdot \text{m}$$

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Test data are stored in the **nl55hz.dat** file in **NOLOAD** directory.

Data matrix: $M := \text{READPRN}(\text{nl55hz})$

Number of points: $N := \text{rows}(M) \cdot 0.95 \quad N = 2.28 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec} \quad T_{\max} = 3.798 \cdot \text{sec}$

$i := 0..N - 1$

Time: $t_i := M_{i,0} \cdot \text{sec} \quad R_1 := 5.8 \cdot \text{ohm} \quad p_m := 2 \quad R_a := 36 \cdot \text{ohm} \quad p_{\text{alt}} := 5$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp} \quad I_{B_i} := M_{i,2} \cdot \text{amp} \quad I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt} \quad U_{BC_i} := M_{i,5} \cdot \text{volt} \quad U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm} \quad \text{Instantaneous power to motor: } P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM} \quad \text{Alternator output frequency: } f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := 72 \cdot \mu\text{F} \quad \text{Voltages across capacitor: } U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

Alternator torque: $T_{\text{alt}_i} := \frac{P_i + R_a \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_{\text{alt}}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

1. MOTOR NO LOAD START-UP TEST (65 Hz.)

(capacitor was in the circuit during whole test)

RPM = $60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$

INPUT CHANNEL MAP

Nm = newton·m

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Test data are stored in the **nl65hz.dat** file in **NOLOAD** directory.

Data matrix: $M := \text{READPRN}(\text{nl65hz})$

Number of points: $N := \text{rows}(M) \cdot 0.95 \quad N = 2.28 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec} \quad T_{\max} = 3.798 \cdot \text{sec}$

$i := 0..N-1$

Time: $t_i := M_{i,0} \cdot \text{sec} \quad R_1 := 5.8 \cdot \text{ohm} \quad p_m := 2 \quad R_a := 36 \cdot \text{ohm} \quad p_{\text{alt}} := 5$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp} \quad I_{B_i} := M_{i,2} \cdot \text{amp} \quad I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt} \quad U_{BC_i} := M_{i,5} \cdot \text{volt} \quad U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm} \quad \text{Instantaneous power to motor: } P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM} \quad \text{Alternator output frequency: } f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := 72 \cdot \mu\text{F} \quad \text{Voltages across capacitor: } U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

Alternator torque: $T_{\text{alt}_i} := \frac{P_i + R_a \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_{\text{alt}}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

1. MOTOR START-UP TEST (load, switchable capacitor)

(35 Hz.)

RPM = $60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$

Nm = newton·m

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Test data are stored in the test-01.dat file in NOLOAD directory.

Data matrix: $M := \text{READPRN}(\text{test_01})$

Number of points: $N := \text{rows}(M) \cdot 0.95$ $N = 2.28 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec}$ $T_{\max} = 3.798 \cdot \text{sec}$

$i := 0..N - 1$

Time: $t_i := M_{i,0} \cdot \text{sec}$ $R_1 := 5.8 \cdot \text{ohm}$ $p_m := 2$ $R_a := 36 \cdot \text{ohm}$ $p_{\text{alt}} := 5$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp}$ $I_{B_i} := M_{i,2} \cdot \text{amp}$ $I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt}$ $U_{BC_i} := M_{i,5} \cdot \text{volt}$ $U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm}$ Instantaneous power to motor: $P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM} \cdot 0.8262$ Alternator output frequency: $f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := \text{if} \left[(t_i > 1.05 \cdot \text{sec}) \cdot (t_i < 3 \cdot \text{sec}), 72 \cdot \mu\text{F}, 10^{10} \cdot \mu\text{F} \right]$ $U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

Alternator torque: $T_{\text{alt}_i} := \frac{P_i + R_a \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_{\text{alt}}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

1. MOTOR START-UP TEST (load, switchable capacitor)

(45 Hz.)

RPM = 60 · Hz · sec · min⁻¹

Nm = newton · m

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Test data are stored in the test-02.dat file in NOLOAD directory.

Data matrix: M := READPRN(test_02)

Number of points: N := rows(M) · 0.95 N = 2.28 · 10³

Maximum time: T_{max} := M_{N-1,0} · sec T_{max} = 3.798 · sec

i := 0..N - 1

Time: t_i := M_{i,0} · sec

R₁ := 5.8 · ohm

P_m := 2

R_a := 36 · ohm

P_{alt} := 5

Instantaneous currents: I_{A_i} := M_{i,1} · amp

I_{B_i} := M_{i,2} · amp

I_{C_i} := M_{i,3} · amp

Instantaneous line-to-line voltages: U_{AB_i} := M_{i,4} · volt

U_{BC_i} := M_{i,5} · volt

U_{CA_i} := M_{i,6} · volt

Load torque: T_{load_i} := M_{i,7} · Nm

Instantaneous power to motor: P_i := M_{i,9} · watt

Motor RPM: Speed_i := M_{i,8} · RPM · 0.8262

Alternator output frequency: f_i := M_{i,10} · Hz

Capacitance: Cap_i := if [(t_i > 1.25 · sec) · (t_i < 3 · sec), 72 · μF, 10¹⁰ · μF]

U_{capA_i} := I_{A_i} · $\frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: T_{em_i} := $\frac{P_i - R_1 \cdot [(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2]}{2 \cdot \pi \cdot f_i} \cdot P_m$

Alternator torque: T_{alt_i} := $\frac{P_i + R_a \cdot [(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2]}{2 \cdot \pi \cdot f_i} \cdot P_{alt}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

1. MOTOR START-UP TEST (load, switchable capacitor)

(55 Hz)

RPM = $60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$

Nm = newton·m

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Test data are stored in the test-03.dat file in NOLOAD directory.

Data matrix: $M := \text{READPRN}(\text{test_03})$

Number of points: $N := \text{rows}(M) \cdot 0.95 \quad N = 2.28 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec} \quad T_{\max} = 3.798 \cdot \text{sec}$

$i := 0..N-1$

Time: $t_i := M_{i,0} \cdot \text{sec} \quad R_1 := 5.8 \cdot \text{ohm} \quad p_m := 2 \quad R_a := 36 \cdot \text{ohm} \quad p_{\text{alt}} := 5$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp} \quad I_{B_i} := M_{i,2} \cdot \text{amp} \quad I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt} \quad U_{BC_i} := M_{i,5} \cdot \text{volt} \quad U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm} \quad \text{Instantaneous power to motor: } P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM} \cdot 0.8262 \quad \text{Alternator output frequency: } f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := \text{if} \left[(t_i > 1.4 \cdot \text{sec}) \cdot (t_i < 2.9 \cdot \text{sec}), 72 \cdot \mu\text{F}, 10^{10} \cdot \mu\text{F} \right] \quad U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

Alternator torque: $T_{\text{alt}_i} := \frac{P_i + R_a \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_{\text{alt}}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

1. MOTOR START-UP TEST (load, switchable capacitor)

(65 Hz)

RPM = $60 \cdot \text{Hz} \cdot \text{sec} \cdot \text{min}^{-1}$

Nm = newton·m

INPUT CHANNEL MAP

1-Time

2-IA

3-IB

4-IC

5-VAB

6-VBC

7-VCA

8-Torque

9-Speed

10 -Power

11-Frequency

Test data are stored in the test-04.dat file in **NOLOAD** directory.

Data matrix: $M := \text{READPRN}(\text{test_04})$

Number of points: $N := \text{rows}(M) \cdot 0.95$ $N = 3.42 \cdot 10^3$

Maximum time: $T_{\max} := M_{N-1,0} \cdot \text{sec}$ $T_{\max} = 5.698 \cdot \text{sec}$

$i := 0..N - 1$

Time: $t_i := M_{i,0} \cdot \text{sec}$ $R_1 := 5.8 \cdot \text{ohm}$ $p_m := 2$ $R_a := 36 \cdot \text{ohm}$ $p_{\text{alt}} := 5$

Instantaneous currents: $I_{A_i} := M_{i,1} \cdot \text{amp}$ $I_{B_i} := M_{i,2} \cdot \text{amp}$ $I_{C_i} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB_i} := M_{i,4} \cdot \text{volt}$ $U_{BC_i} := M_{i,5} \cdot \text{volt}$ $U_{CA_i} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load}_i} := M_{i,7} \cdot \text{Nm}$ Instantaneous power to motor: $P_i := M_{i,9} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,8} \cdot \text{RPM} \cdot 0.8262$ Alternator output frequency: $f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $\text{Cap}_i := \text{if} \left[(t_i > 1.5 \cdot \text{sec}) \cdot (t_i < 5 \cdot \text{sec}), 72 \cdot \mu\text{F}, 10^{10} \cdot \mu\text{F} \right]$ $U_{\text{cap}A_i} := I_{A_i} \cdot \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i}$

Electromagnetic torque: $T_{\text{em}_i} := \frac{P_i - R_1 \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_m$

Alternator torque: $T_{\text{alt}_i} := \frac{P_i + R_a \cdot \left[(I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot p_{\text{alt}}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

APPENDIX I: Validation Results for Dynamic Tests of Alternator / Induction Motor System

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\noload01.dat.

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Motor torque - Column 7

Alternator torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

35 Hz

Data matrix: $B := \text{READPRN}(\text{noload01})$

Number of rows: $L := \text{rows}(B)$ $L = 1.278 \cdot 10^3$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 2 \cdot \text{sec}$

$j := 0 \dots L - 1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz}$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$U_{A.\text{mot.model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\noload02.dat.

Time - Column 1
 Alternator frequency - Column 2
 Motor RPM - Column 3
 Stator current - Column 4
 Motor input voltage - Column 5
 Alternator output voltage - Column 6
 Motor torque - Column 7
 Alternator torque - Column 8
 Motor input power - Column 9
 Voltage across capacitors - Column 10

45 Hz

Data matrix: $B := \text{READPRN}(\text{noload02})$

Number of rows: $L := \text{rows}(B)$ $L = 1.131 \cdot 10^3$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 1 \cdot \text{sec}$

$j := 0..L - 1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz}$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$U_{A.\text{mot.model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\noload03.dat.

Time - Column 1
 Alternator frequency - Column 2
 Motor RPM - Column 3
 Stator current - Column 4
 Motor input voltage - Column 5
 Alternator output voltage - Column 6
 Motor torque - Column 7
 Alternator torque - Column 8
 Motor input power - Column 9
 Voltage across capacitors - Column 10

55 Hz

Data matrix: $B := \text{READPRN}(\text{noload03})$

Number of rows: $L := \text{rows}(B)$ $L = 863$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 1 \cdot \text{sec}$

$j := 0 \dots L - 1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz}$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$U_{A.\text{mot.model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\lice\dynamic\modeldata\noload04.dat.

Time - Column 1
 Alternator frequency - Column 2
 Motor RPM - Column 3
 Stator current - Column 4
 Motor input voltage - Column 5
 Alternator output voltage - Column 6
 Motor torque - Column 7
 Alternator torque - Column 8
 Motor input power - Column 9
 Voltage across capacitors - Column 10

65 Hz

Data matrix: $B := \text{READPRN}(\text{noload04})$

Number of rows: $L := \text{rows}(B)$ $L = 964$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 1 \cdot \text{sec}$

$j := 0..L - 1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz}$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$U_{A.\text{mot.model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\noload01.dat.

Time - Column 1
 Alternator frequency - Column 2
 Motor RPM - Column 3
 Stator current - Column 4
 Motor input voltage - Column 5
 Alternator output voltage - Column 6
 Motor torque - Column 7
 Alternator torque - Column 8
 Motor input power - Column 9
 Voltage across capacitors - Column 10

35 Hz

Data matrix: $B := \text{READPRN}(\text{loadst01})$

Number of rows: $L := \text{rows}(B)$ $L = 1.849 \cdot 10^3$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 3 \cdot \text{sec}$

$j := 0..L - 1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz} \cdot 0.945$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$U_{A.\text{mot.model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

$\Delta T := 0.62 \cdot \text{sec}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\noload02.dat.

Time - Column 1
 Alternator frequency - Column 2
 Motor RPM - Column 3
 Stator current - Column 4
 Motor input voltage - Column 5
 Alternator output voltage - Column 6
 Motor torque - Column 7
 Alternator torque - Column 8
 Motor input power - Column 9
 Voltage across capacitors - Column 10

45 Hz

Data matrix: $B := \text{READPRN}(\text{loadst02})$

Number of rows: $L := \text{rows}(B)$ $L = 2.355 \cdot 10^3$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 2.5 \cdot \text{sec}$

$j := 0..L - 1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz}$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$U_{A.\text{model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

$\Delta T := 0.8 \cdot \text{sec}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\moload04.dat.

Time - Column 1
 Alternator frequency - Column 2
 Motor RPM - Column 3
 Stator current - Column 4
 Motor input voltage - Column 5
 Alternator output voltage - Column 6
 Motor torque - Column 7
 Alternator torque - Column 8
 Motor input power - Column 9
 Voltage across capacitors - Column 10

55 Hz

Data matrix: $B := \text{READPRN}(\text{loadst03})$

Number of rows: $L := \text{rows}(B)$ $L = 2.185 \cdot 10^3$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 3 \cdot \text{sec}$

$j := 0..L-1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz}$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$U_{A.\text{mot.model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

$\Delta T := 0.88 \cdot \text{sec}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\noload04.dat.

Time - Column 1
 Alternator frequency - Column 2
 Motor RPM - Column 3
 Stator current - Column 4
 Motor input voltage - Column 5
 Alternator output voltage - Column 6
 Motor torque - Column 7
 Alternator torque - Column 8
 Motor input power - Column 9
 Voltage across capacitors - Column 10

65 Hz

Data matrix: $B := \text{READPRN}(\text{loadst04})$

Number of rows: $L := \text{rows}(B)$ $L = 3.506 \cdot 10^3$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 5 \cdot \text{sec}$

$j := 0..L - 1$

$t_{\text{model}_j} := B_{j,0} \cdot \text{sec}$

$T_{\text{alt.model}_j} := B_{j,6} \cdot \text{Nm}$

$f_{\text{model}_j} := B_{j,1} \cdot \text{Hz}$

$T_{\text{mot.model}_j} := B_{j,7} \cdot \text{Nm}$

$\text{Speed}_{\text{model}_j} := B_{j,2} \cdot \text{RPM}$

$I_{A.\text{model}_j} := B_{j,3} \cdot \text{amp}$

$P_{\text{model}_j} := B_{j,8} \cdot \text{kW}$

$U_{A.\text{mot.model}_j} := B_{j,4} \cdot \text{volt}$

$U_{\text{capA.model}_j} := B_{j,9} \cdot \text{volt}$

$U_{A.\text{alt.model}_j} := B_{j,5} \cdot \text{volt}$

$\Delta T := 0.2 \cdot \text{sec}$

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

MOTOR START-UP

APPENDIX J: Simulations of Different Approaches to Start-up Problem

1. MODELED DYNAMIC BEHAVIOR OF DIFFERENT APPROACHES TO START-UP PROBLEM**Base case: 1. No-Load**

Data are stored in c:\matlab\ice\modeldat\noload01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{nofollow01})$ Number of rows: $L := \text{rows}(B)$ $L = 2.569 \cdot 10^3$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 5 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ **MOTOR START-UP**

— Motor
..... Load

— Alternator
..... Wind Rotor

MOTOR START-UP

Base case: 2. Constant Load

Data are stored in c:\matlab\ice\model\dat\load01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{load01})$ Number of rows: $L := \text{rows}(B)$ $L = 26$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 0.022 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{W_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ **MOTOR START-UP**

— Motor
--- Load

— Alternator
--- Wind Rotor

MOTOR START-UP

Switched capacitor: 1. Constant Load

Data are stored in c:\matlab\ice\modeldat\loadc01.dat.

Nm := newton-m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Capacitance:

 $C := 200 \cdot \mu\text{F}$

Data matrix:

 $B := \text{READPRN}(\text{loadc01})$

Number of rows:

 $L := \text{rows}(B) \quad L = 801$

Maximum time:

 $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 0.5 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec} \quad f_i := B_{i,1} \cdot \text{Hz} \quad \text{Speed}_i := B_{i,2} \quad I_{A_i} := B_{i,3} \cdot \text{amp} \quad U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt} \quad T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm} \quad T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm} \quad P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm} \quad T_{\text{load}_i} := B_{i,11} \cdot \text{Nm} \quad V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}} \quad U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ Capacitor is off when $t > 0.2 \text{ sec}$. **MOTOR START-UP**

— Motor
--- Load

— Alternator
--- Wind Rotor

MOTOR START-UP

Switched capacitor: 2. Sinusoidal Load

Data are stored in c:\matlab\ice\modeldat\load~c01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Capacitance: $C := 200 \cdot \mu\text{F}$ Data matrix: $B := \text{READPRN}(\text{loadsinc01})$ Number of rows: $L := \text{rows}(B)$ $L = 799$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 0.5 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ Capacitor is off when $t > 0.2 \text{ sec}$. **MOTOR START-UP**

— Motor
— Load

— Alternator
— Wind Rotor

MOTOR START-UP

CLUTCH: 1. Constant Load

Data are stored in c:\matlab\ice\modeldat\loadcl01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{loadcl01})$ Number of rows: $L := \text{rows}(B)$ $L = 5.074 \cdot 10^3$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 8 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ **MOTOR START-UP**

— Motor
— Load

— Alternator
— Wind Rotor

MOTOR START-UP

CLUTCH: 2. Sinusoidal Load

Data are stored in c:\matlab\ice\modeldat\loa~cl01.dat.

Nm := newton-m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{loadsincl01})$ Number of rows: $L := \text{rows}(B)$ $L = 5.104 \cdot 10^3$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 8 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{W_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ **MOTOR START-UP**

— Motor
--- Load

— Alternator
--- Wind Rotor

MOTOR START-UP

2. MODELED DYNAMIC BEHAVIOR OF DIFFERENT APPROACHES TO START-UP PROBLEM

Basecase: 1. No-Load

Data are stored in c:\matlab\ice\modeldat\noload01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{noload02})$

Number of rows: $L := \text{rows}(B)$ $L = 990$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 2 \cdot \text{sec}$

$i := 0..L-1$

$t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$

$U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$

$T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$

$\text{Speed}_1 := \text{Speed}$ $t_1 := t$ $N_1 := L$

MOTOR START-UP

— Motor
--- Load

— Alternator
--- Wind Rotor

MOTOR START-UP

Basecase: 2. Constant Load

Data are stored in c:\matlab\ice\modeldat\load01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{load02})$ Number of rows: $L := \text{rows}(B)$ $L = 26$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 0.05 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ $\text{Speed}_2 := \text{Speed}$ $t_2 := t$ $N_2 := L$ **MOTOR START-UP**

— Motor
— Load

— Alternator
— Wind Rotor

MOTOR START-UP

Switched capacitor: 1. Constant Load

Data are stored in c:\matlab\ice\modeldat\loadc01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Capacitance:

 $C := 1500 \cdot \mu\text{F}$

Data matrix:

 $B := \text{READPRN}(\text{loadc02})$

Number of rows:

 $L := \text{rows}(B)$ $L = 629$

Maximum time:

 $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 1 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec} \quad f_i := B_{i,1} \cdot \text{Hz} \quad \text{Speed}_i := B_{i,2} \quad I_{A_i} := B_{i,3} \cdot \text{amp} \quad U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt} \quad T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm} \quad T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm} \quad P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm} \quad T_{\text{load}_i} := B_{i,11} \cdot \text{Nm} \quad V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}} \quad U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ $\text{Speed}_3 := \text{Speed} \quad t_3 := t \quad N_3 := L$ Capacitor is off when $t > 0.2 \text{ sec}$. **MOTOR START-UP**

— Motor
--- Load

— Alternator
--- Wind Rotor

MOTOR START-UP

Switched capacitor: 2. Sinusoidal Load

Data are stored in c:\matlab\ice\model\dat\load~c01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Capacitance: $C := 1500 \cdot \mu\text{F}$

Data matrix: $B := \text{READPRN}(\text{loadsinc02})$

Number of rows: $L := \text{rows}(B)$ $L = 622$

Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 1 \cdot \text{sec}$

$i := 0..L - 1$

$t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$

$U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$

$T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$

$\text{Speed}_4 := \text{Speed}$ $t_4 := t$ $N_4 := L$

Capacitor is off when $t > 0.2 \text{ sec}$.

MOTOR START-UP

— Motor
— Load

— Alternator
— Wind Rotor

MOTOR START-UP

CLUTCH: 1. Constant Load

Data are stored in c:\matlab\ice\modeldat\loadcl01.dat.

Nm := newton-m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: B := READPRN(loadcl02)

Number of rows: L := rows(B) L = 1.011·10³Maximum time: T_{max} := B_{L-1,0}·sec T_{max} = 2·sec

i := 0..L - 1

t_i := B_{i,0}·sec f_i := B_{i,1}·Hz Speed_i := B_{i,2} I_{A_i} := B_{i,3}·amp U_{A_i} := B_{i,4}·voltU_{Aalt_i} := B_{i,5}·volt T_{alt_i} := B_{i,6}·Nm T_{mot_i} := B_{i,7}·Nm P_i := B_{i,8}·kWT_{w_i} := B_{i,10}·Nm T_{load_i} := B_{i,11}·Nm V_i := B_{i,12}· $\frac{\text{m}}{\text{sec}}$ U_{capA_i} := B_{i,9}·voltSpeed₅ := Speed t₅ := t N₅ := L **MOTOR START-UP**

— Motor
--- Load

— Alternator
--- Wind Rotor

MOTOR START-UP

CLUTCH: 2. Sinusoidal Load

Data are stored in c:\matlab\ice\modeldat\loa~cl01.dat.

Nm := newton·m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{loadsincl02})$ Number of rows: $L := \text{rows}(B)$ $L = 1.011 \cdot 10^3$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 2 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ $\text{Speed}_6 := \text{Speed}$ $t_6 := t$ $N_6 := L$ **MOTOR START-UP**

— Motor
 --- Load

— Alternator
 --- Wind Rotor

MOTOR START-UP

SCROLL COMPRESSOR: 1. Constant Load

Data are stored in c:\matlab\ice\modeldat\loadsc01.dat.

Nm := newton-m

Time - Column 1

Alternator frequency - Column 2

Motor RPM - Column 3

Stator current - Column 4

Motor input voltage - Column 5

Alternator output voltage - Column 6

Alternator torque - Column 7

Motor torque - Column 8

Motor input power - Column 9

Voltage across capacitors - Column 10

Wind rotor torque - Column 11

Motor load torque - Column 12

Data matrix: $B := \text{READPRN}(\text{loadsc02})$ Number of rows: $L := \text{rows}(B)$ $L = 1.654 \cdot 10^3$ Maximum time: $T_{\max} := B_{L-1,0} \cdot \text{sec}$ $T_{\max} = 4 \cdot \text{sec}$ $i := 0..L - 1$ $t_i := B_{i,0} \cdot \text{sec}$ $f_i := B_{i,1} \cdot \text{Hz}$ $\text{Speed}_i := B_{i,2}$ $I_{A_i} := B_{i,3} \cdot \text{amp}$ $U_{A\text{mot}_i} := B_{i,4} \cdot \text{volt}$ $U_{A\text{alt}_i} := B_{i,5} \cdot \text{volt}$ $T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm}$ $T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm}$ $P_i := B_{i,8} \cdot \text{kW}$ $T_{w_i} := B_{i,10} \cdot \text{Nm}$ $T_{\text{load}_i} := B_{i,11} \cdot \text{Nm}$ $V_i := B_{i,12} \cdot \frac{\text{m}}{\text{sec}}$ $U_{\text{capA}_i} := B_{i,9} \cdot \text{volt}$ $\text{Speed}_7 := \text{Speed}$ $t_7 := t$ $N_7 := L$ **MOTOR START-UP**

— Motor
--- Load

— Alternator
--- Wind Rotor

MOTOR START-UP

APPENDIX K: Cost of Ice Analysis

Fuel Cost = \$1.50/gallon

Note: Wind-Only and Wind-Diesel cases include icemaker modification cost of \$5,000

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1.	2. REPORT DATE July 1998	3. REPORT TYPE AND DATES COVERED Technical Report	
4. TITLE AND SUBTITLE Wind-Electric Icemaking Project: Analysis and Dynamometer Testing Volume II			5. FUNDING NUMBERS C: TA: WE805020
6. AUTHOR(S) Rick Holz, P.E., Vahan Gervorgian, Ph.D., Steve Drouilhet, P.E., Ed Muljadi, Ph.D.			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Wind Technology Center National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393			10. SPONSORING/MONITORING AGENCY REPORT NUMBER TP-500-24010
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161			12b. DISTRIBUTION CODE UC-1213
13. ABSTRACT (Maximum 200 words) The wind/hybrid systems group at the national Renewable Energy Laboratory has been researching the most practical and cost-effective methods for producing ice from off-grid wind-electric power systems. The first phase of the project, conducted in 1993-1994, included full-scale dynamometer and field testing of two different electric ice makers directly connected to a permanent magnet alternator. The results of that phase were encouraging and the second phase of the project was launched in which steady-state and dynamic numerical models of these systems were developed and experimentally validated. The third phase of the project was the dynamometer testing of the North Star ice maker, which is powered by a 12-kilowatt Bergey Windpower Company, Inc., alternator. This report describes both the second and third project phases. Also included are detailed economic analyses and a discussion of the future prospects of wind-electric ice-making systems. The main report is contained in Volume I. Volume II consists of the report appendices, which include the actual computer programs used in the analysis and the detailed test results.			
14. SUBJECT TERMS renewable energy; wind energy; icemaking			15. NUMBER OF PAGES
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL