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

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Volume II
Table of Contents

Appendix A: Mathematical Description of Steady State Model
Appendix B: Mathematical Description of Dynamic Model
Appendix C: Bench-Scale Test Machinery Specifications
Appendix D: Detailed Results for Tests 1 and 2 (Machine Parameter Determinations)
Appendix E: Detailed Results for Test 3 (Steady-State Line-Connected Induction Motor)
Appendix F: Detailed Results for Test 4 (Dynamic Line-Connected Induction Motor)
Appendix G: Detailed Results for Test 5 (Steady-State Alternator / Induction Motor System)
Appendix H: Detailed Results for Test 6 (Dynamic Alternator / Induction Motor System)
Appendix I: Results for Dynamic Tests of Alternator / Induction Motor System
Appendix J: Simulations of Different Approaches to Start-up Problem
Appendix K: Cost of Ice Analysis
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
- \( L_a \) - 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):
\[ Z_a(f) := R_a + j \cdot \omega_e(f) \cdot L \]

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):
Capacitor impedance (ohm):
\[ Z_{c1}(f, C_1) := \frac{-j}{\omega_e(f) \cdot C_1} \]

Total circuit impedance (ohm):
\[ Z_{tot}(f, s, C) := Z_s(f) + Z_{c1}(f, C_1) + Z_m(f, s) \]

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):
\[ P_{alt}(f, s, C) := 3 \cdot \text{Re}(I_a(f, s, C) \cdot V_{alt}(f, s, C)) \]

Alternator electromagnetic power (watt):
\[ P_{alt.em}(f, s, C) := P_{alt}(f, s, C) + 3 \cdot (|I_a(f, s, C)|^2) \cdot R_a \]

Alternator electromagnetic torque (Nm):
\[ T_{alt}(f, s, C) := P_{alt.em}(f, s, C) \cdot \frac{\omega_e(f)}{P_{alt}} \]

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):
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:

\[ P_{rotor}(V, f) = \frac{1}{2} \rho A C_p(\lambda) V \]

where: \( \rho \) - air density (kg/m\(^3\)); \( A \) - swept area (m\(^2\)); \( C_p(\lambda) \) - coefficient of performance as a function of tip speed ratio \( \lambda \); \( V \) - 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 - $I_{\text{rated}}$
- Voltage - $U_{\text{rated}}$
- Frequency - $f_{\text{rated}}$

Number of alternator pairs of poles - $p_{\text{alt}}$
Number of motor pairs of poles - $p_{\text{mot}}$

| Base voltage (volt): $U_{\text{base}}$ | Base resistance (ohm): $Z_{\text{base}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{base}} := U_{\text{rated}} \sqrt{2}$</td>
<td>$Z_{\text{base}} := \frac{U_{\text{base}}}{I_{\text{base}}}$</td>
</tr>
</tbody>
</table>

| Base current (amp): $I_{\text{base}}$ | Base inductance (henry): $L_{\text{base}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{base}} := I_{\text{rated}} \sqrt{2}$</td>
<td>$L_{\text{base}} := \frac{Z_{\text{base}}}{\omega_{\text{base}}}$</td>
</tr>
</tbody>
</table>

| Base power (watt): $P_{\text{base}}$ | Base capacitance (farad): $C_{\text{base}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{base}} := \frac{3}{2} U_{\text{base}} I_{\text{base}}$</td>
<td>$C_{\text{base}} := \frac{1}{\omega_{\text{base}} Z_{\text{base}}}$</td>
</tr>
</tbody>
</table>

| Base frequency: $f_{\text{base}}$ | Base torque (Nm): $T_{\text{base}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\text{base}} := f_{\text{rate}}$</td>
<td>$T_{\text{base}} := \frac{P_{\text{base}}}{\Omega_{\text{base}}}$</td>
</tr>
</tbody>
</table>

| Base electrical angular speed (rad/sec): $\omega_{\text{base}}$ | Base moment of inertia: $J_{\text{base}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{\text{base}} := 2 \pi f_{\text{base}}$</td>
<td>$J_{\text{base}} := \frac{p_{\text{alt}} T_{\text{base}}}{\frac{\omega_{\text{base}}}{2}}$</td>
</tr>
</tbody>
</table>

| Base angular mechanical speed (rad/sec): $\Omega_{\text{base}}$ | Base charge: $Q_{\text{base}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_{\text{base}} := \frac{\omega_{\text{base}}}{p_{\text{alt}}}$</td>
<td>$Q_{\text{base}} := I_{\text{base}} t_{\text{base}}$</td>
</tr>
</tbody>
</table>

| Base RPM: $N_{\text{base}}$ | Base time: $t_{\text{base}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{base}} := \frac{60 f_{\text{base}}}{p_{\text{alt}}}$</td>
<td>$t_{\text{base}} := \frac{1}{\omega_{\text{base}}}$</td>
</tr>
</tbody>
</table>
2. Input parameters

<table>
<thead>
<tr>
<th>Parameters in p.u.</th>
<th>Alternator</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance:</td>
<td>$R_{alt}(\text{ohm})$</td>
<td>$R_{1.mot}(\text{ohm})$</td>
</tr>
<tr>
<td></td>
<td>$R_{alt} := \frac{Z_{base}}{}$</td>
<td>$R_{1.mot} := \frac{Z_{base}}{}$</td>
</tr>
<tr>
<td>Leakage inductance:</td>
<td>$L_{\sigma.alt}(\text{henry})$</td>
<td>$L_{\sigma.1.mot}(\text{henry})$</td>
</tr>
<tr>
<td></td>
<td>$L_{\sigma.alt} := \frac{L_{base}}{}$</td>
<td>$L_{\sigma.1.mot} := \frac{L_{base}}{}$</td>
</tr>
<tr>
<td>Direct-axis synchronous inductance:</td>
<td>$L_{md}(\text{henry})$</td>
<td>$L_{\sigma.2.mot}(\text{henry})$</td>
</tr>
<tr>
<td></td>
<td>$L_{md} := \frac{2L_{ad}(\text{henry})}{3}$</td>
<td>$L_{\sigma.2.mot} := \frac{L_{ad}(\text{henry})}{L_{base}}$</td>
</tr>
<tr>
<td>Quadrature-axis synchronous inductance:</td>
<td>$L_{mq}(\text{henry})$</td>
<td>$L_{m}(\text{henry})$</td>
</tr>
<tr>
<td></td>
<td>$L_{mq} := \frac{2L_{aq}(\text{henry})}{3}$</td>
<td>$L_{m} := \frac{L_{aq}(\text{henry})}{L_{base}}$</td>
</tr>
<tr>
<td>Alternator moment of inertia:</td>
<td>$J_{alt}(\text{kg-m}^2)$</td>
<td>$L_{m}(\text{henry})$</td>
</tr>
<tr>
<td></td>
<td>$J_{alt} := \frac{J_{base}}{}$</td>
<td>$L_{m} := \frac{J_{base}}{}$</td>
</tr>
<tr>
<td>Driving device moment of inertia:</td>
<td>$J_{dr}(\text{kg-m}^2)$</td>
<td>$L_{m}(\text{henry})$</td>
</tr>
<tr>
<td></td>
<td>$J_{dr} := \frac{J_{base}}{}$</td>
<td>$L_{m} := \frac{J_{base}}{}$</td>
</tr>
<tr>
<td>Alternator volt/hertz ratio:</td>
<td>$K(\text{volt/Hz})$</td>
<td>$R_{o}(\text{ohm})$</td>
</tr>
<tr>
<td></td>
<td>$K := \frac{U_{base}}{2f_{bas}}$</td>
<td>$R_{o} := \frac{J_{base}}{}$</td>
</tr>
<tr>
<td>Capacitance:</td>
<td>$C_{base}(\text{farad})$</td>
<td>$J_{mot}(\text{kg-m}^2)$</td>
</tr>
<tr>
<td></td>
<td>$C := \frac{C_{base}}{J_{load}(\text{kg-m}^2)}$</td>
<td>$J_{load} := \frac{J_{load}(\text{kg-m}^2)}{J_{base}}$</td>
</tr>
</tbody>
</table>
3. Initial conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Designation (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor initial rotor angle:</td>
<td>( \varphi_{\text{mot}0} )</td>
</tr>
<tr>
<td>Motor initial angular mechanical speed:</td>
<td>( \Omega_{\text{mot}0} )</td>
</tr>
<tr>
<td>Alternator initial rotor angle:</td>
<td>( \varphi_{\text{alt}0} )</td>
</tr>
<tr>
<td>Alternator initial angular mechanical speed (in p.u. this value is equal to alternator output frequency):</td>
<td>( \Omega_{\text{alt}0} )</td>
</tr>
<tr>
<td>Charge through capacitor of phase “A”:</td>
<td>( Q_{A0} )</td>
</tr>
<tr>
<td>Charge through capacitor of phase “B”:</td>
<td>( Q_{B0} )</td>
</tr>
<tr>
<td>Charge through capacitor of phase “C”:</td>
<td>( Q_{C0} )</td>
</tr>
<tr>
<td>Alternator phase “A” initial current:</td>
<td>( I_{A0} )</td>
</tr>
<tr>
<td>Alternator phase “B” initial current:</td>
<td>( I_{B0} )</td>
</tr>
<tr>
<td>Alternator phase “C” initial current:</td>
<td>( I_{C0} )</td>
</tr>
<tr>
<td>Motor rotor phase “a” initial current:</td>
<td>( I_{a0} )</td>
</tr>
<tr>
<td>Motor rotor phase “b” initial current:</td>
<td>( I_{b0} )</td>
</tr>
<tr>
<td>Motor rotor phase “c” initial current:</td>
<td>( I_{c0} )</td>
</tr>
</tbody>
</table>

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):

\[
L_{A,\text{alt}} = L_{\text{alt.av}} + L_{\text{alt.var}} \cos(2\gamma_{\text{alt}}) + L_{\sigma,\text{al}}
\]

\[
pL_{A,\text{alt}} = -2\Omega_{\text{alt}} L_{\text{alt.var}} \sin(2\gamma_{\text{alt}})
\]

\[
L_{B,\text{alt}} = L_{\text{alt.av}} + L_{\text{alt.var}} \cos(2\gamma_{\text{alt}} + \frac{2\pi}{3}) + L_{\sigma,\text{al}}
\]

\[
pL_{B,\text{alt}} = -2\Omega_{\text{alt}} L_{\text{alt.var}} \sin(2\gamma_{\text{alt}} + \frac{2\pi}{3})
\]

\[
L_{C,\text{alt}} = L_{\text{alt.av}} + L_{\text{alt.var}} \cos(2\gamma_{\text{alt}} + \frac{4\pi}{3}) + L_{\sigma,\text{al}}
\]

\[
pL_{C,\text{alt}} = -2\Omega_{\text{alt}} L_{\text{alt.var}} \sin(2\gamma_{\text{alt}} + \frac{4\pi}{3})
\]
Mutual inductances between stator phases and their time derivatives:

\[
\begin{align*}
L_{AB,\text{alt}} &= -\frac{L_{\text{alt,av}}}{2} + L_{\text{alt,av}} \cos \left(2\gamma_{\text{alt}} + \frac{4}{3}\pi \right) \\
L_{AC,\text{alt}} &= -\frac{L_{\text{alt,av}}}{2} + L_{\text{alt,av}} \cos \left(2\gamma_{\text{alt}} + \frac{2}{3}\pi \right) \\
L_{BC,\text{alt}} &= -\frac{L_{\text{alt,av}}}{2} + L_{\text{alt,av}} \cos \left(2\gamma_{\text{alt}} \right)
\end{align*}
\]

Time derivatives of mutual inductances between stator and PM rotor:

\[
\begin{align*}
pL_{Af} &= -\frac{3}{2} \cdot 2\cdot \Omega_{\text{alt}} v L \cdot m_d \sin \left(2\gamma_{\text{alt}} \right) \\
pL_{Bf} &= -\frac{3}{2} \cdot 2\cdot \Omega_{\text{alt}} v L \cdot m_d \sin \left(2\gamma_{\text{alt}} + \frac{4}{3}\pi \right) \\
pL_{Cf} &= -\frac{3}{2} \cdot 2\cdot \Omega_{\text{alt}} v L \cdot m_d \sin \left(2\gamma_{\text{alt}} + \frac{2}{3}\pi \right)
\end{align*}
\]

E.M.F. induced in stator phases:

\[
\begin{align*}
E_A &= K \cdot \Omega_{\text{alt}} \sin \left(\gamma_{\text{alt}} \right) \\
E_B &= K \cdot \Omega_{\text{alt}} \sin \left(\gamma_{\text{alt}} + \frac{4}{3}\pi \right) \\
E_C &= K \cdot \Omega_{\text{alt}} \sin \left(\gamma_{\text{alt}} + \frac{2}{3}\pi \right)
\end{align*}
\]

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

Stator inductances:

\[
\begin{align*}
L_{A,\text{mot}} &= L_m + L_{\sigma 1.\text{mo}} \\
L_{B,\text{mot}} &= L_m + L_{\sigma 1.\text{mo}} \\
L_{C,\text{mot}} &= L_m + L_{\sigma 1.\text{mo}}
\end{align*}
\]

Stator mutual inductances:

\[
\begin{align*}
L_{AB,\text{mot}} &= \frac{L}{2} \\
L_{AC,\text{mot}} &= \frac{L}{2} \\
L_{BC,\text{mot}} &= \frac{L}{2}
\end{align*}
\]

Rotor inductances:

\[
\begin{align*}
L_{a,\text{mot}} &= L_m + L_{\sigma 2.\text{mo}} \\
L_{b,\text{mot}} &= L_m + L_{\sigma 2.\text{mo}} \\
L_{c,\text{mot}} &= L_m + L_{\sigma 2.\text{mo}}
\end{align*}
\]

Rotor mutual inductances:

\[
\begin{align*}
L_{ab,\text{mot}} &= \frac{L}{2} \\
L_{ac,\text{mot}} &= \frac{L}{2} \\
L_{bc,\text{mot}} &= \frac{L}{2}
\end{align*}
\]
Mutual inductances between stator and rotor windings and their time derivatives:

\[ L_{\text{Aa}} := L_m \cos(\gamma_{\text{mot}}) \]
\[ L_{\text{Bb}} := L_m \cos(\gamma_{\text{mot}}) \]
\[ L_{\text{Cc}} := L_m \cos(\gamma_{\text{mot}}) \]
\[ pL_{\text{Aa}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin(\gamma_{\text{mot}}) \]
\[ pL_{\text{Bb}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin(\gamma_{\text{mot}}) \]
\[ pL_{\text{Cc}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin(\gamma_{\text{mot}}) \]

\[ L_{\text{Ab}} := L_m \cos\left(\gamma_{\text{mot}} + \frac{2}{3}\pi\right) \]
\[ L_{\text{Bc}} := L_m \cos\left(\gamma_{\text{mot}} + \frac{2}{3}\pi\right) \]
\[ L_{\text{Ca}} := L_m \cos\left(\gamma_{\text{mot}} + \frac{2}{3}\pi\right) \]
\[ pL_{\text{Ab}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{2}{3}\pi\right) \]
\[ pL_{\text{Bc}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{2}{3}\pi\right) \]
\[ pL_{\text{Ca}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{2}{3}\pi\right) \]

\[ L_{\text{Ac}} := L_m \cos\left(\gamma_{\text{mot}} + \frac{4}{3}\pi\right) \]
\[ L_{\text{Ba}} := L_m \cos\left(\gamma_{\text{mot}} + \frac{4}{3}\pi\right) \]
\[ L_{\text{Cb}} := L_m \cos\left(\gamma_{\text{mot}} + \frac{4}{3}\pi\right) \]
\[ pL_{\text{Ac}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{4}{3}\pi\right) \]
\[ pL_{\text{Ba}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{4}{3}\pi\right) \]
\[ pL_{\text{Cb}} := \frac{P_{\text{mot}}}{P_{\text{alt}}} \Omega_{\text{mot}} L_m \sin\left(\gamma_{\text{mot}} + \frac{4}{3}\pi\right) \]

6. Matrices

Matrix of inductances:

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

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

Matrix of voltages:

\[
U := \begin{bmatrix}
E_A - \frac{1}{C} Q_A \\
E_B - \frac{1}{C} Q_B \\
E_C - \frac{1}{C} Q_C
\end{bmatrix}
\]

Matrixes A and B:

\[
A := L^{-1} \\
B := L^{-1} \cdot p
\]

Matrixes C and D:

\[
C := \begin{bmatrix}
I_A & I_B & I_C & A_0 & A_1 & A_2 & A_3 & A_4 & A_5
\end{bmatrix}
\]

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

Matrix of currents and charges through capacitors:

\[
X := \begin{bmatrix}
Q_A \\
Q_B \\
Q_C \\
I_A \\
I_B \\
I_C
\end{bmatrix}
\]

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

\[
pX := \begin{bmatrix}
pQ_A \\
pQ_B \\
pQ_C \\
pI_A \\
pI_B \\
pI_C
\end{bmatrix}
\]

Matrix G:

\[
G := C - D \cdot X
\]
7. Voltages, powers and electromagnetic torques:

Motor input phase voltages:

\[ U_{A,\text{mot}} = E_A - (R_{alt} + pL_{A,\text{alt}})I_A - pL_{AB,\text{alt}}I_B - pL_{AC,\text{alt}}I_C - L_{A,\text{alt}}F_3 - L_{AB,\text{alt}}F_4 - L_{AC,\text{alt}}F_5 - \frac{Q_A}{C} \]

\[ U_{B,\text{mot}} = E_B - pL_{AB,\text{alt}}I_A - (R_{alt} + pL_{B,\text{alt}})I_B - pL_{BC,\text{alt}}I_C - L_{AB,\text{alt}}F_3 - L_{B,\text{alt}}F_4 - L_{BC,\text{alt}}F_5 - \frac{Q_B}{C} \]

\[ U_{C,\text{mot}} = E_C - pL_{AC,\text{alt}}I_A - pL_{BC,\text{alt}}I_B - (R_{alt} + pL_{C,\text{alt}})I_C - L_{AC,\text{alt}}F_3 - L_{BC,\text{alt}}F_4 - L_{C,\text{alt}}F_5 - \frac{Q_C}{C} \]

Input power to motor (alternator output power):

\[ P_1 = \frac{2}{3} (U_{A,\text{mot}}I_A + U_{B,\text{mot}}I_B + U_{C,\text{mot}}I_C) \]

Electrical losses in alternator stator:

\[ P_{\text{el,alt}} = \frac{2}{3} R_{alt} \left( I_A^2 + I_B^2 + I_C^2 \right) \]

Electrical losses in motor stator:

\[ P_{\text{el,\text{mot}}} = \frac{2}{3} R_{\text{mot}} \left( I_A^2 + I_B^2 + I_C^2 \right) \]

Alternator electromagnetic torque:

\[ T_{\text{em,alt}} = \frac{P_1 + P_{\text{el,alt}}}{\Omega_{\text{alt}}} \]

Motor electromagnetic torque:

\[ T_{\text{em,mot}} = \frac{P_{\text{mot}} P_1 - P_{\text{el,\text{mot}}}}{P_{\text{alt}}} \frac{\Omega_{\text{alt}}}{\Omega_{\text{mot}}} \]

8. Alternator driving torque
a) Wind rotor

Parameters: \( r \) - radius, \( \text{Area} \) - swept area, \( J_{\text{rotor}} \) - moment of inertia, \( \rho \) - air density

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

Tip-speed ratio as a function of time:

\[ \lambda(t) = \frac{r \Omega_{\text{alt}} \Omega_{\text{base}}}{V(t)} \]
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:

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

b) Driving motor

Parameters: \( J_{dr.mot} \) - 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:

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

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:

\[ T_{\text{friction}}(\Omega_{mot}) := H \cdot \Omega_{mot} \]

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:

\[ T_{\text{oscillating}}(\Omega_{mot} \cdot t) = \Delta T \cdot \cos(F(\Omega_{mot} \cdot t)) \]

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

So the motor load torque:

\[ T_{\text{load}}(\Omega_{mot} \cdot t) = T_{\text{friction}}(\Omega_{mot}) + T_{\text{load.average}} + T_{\text{oscillating}}(\Omega_{mot} \cdot t) \]
10. System of differential equations:

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

\[ p \dot{\Omega}_{alt} = \frac{T_{rotor}(t) - T_{em.al}}{J_{alt} + J_{rotor}} \]

a) In case of wind rotor:

\[ p \dot{\Omega}_{alt} = \frac{T_{rotor} - T_{em.al}}{J_{alt} + J_{rotor}} \]

b) In case of driving motor:

\[ p \dot{\Omega}_{alt} = \frac{T_{dr.mot}(f, \Omega_{alt}) - T_{em.al}}{J_{alt} + J_{dr.mot}} \]

Motor equations of motion:

\[ p \dot{\Omega}_{mot} = \frac{P_{mot}}{P_{alt}} \cdot \Omega_{mot} \]

\[ p \dot{\Omega}_{mot} = \frac{T_{em.mot} - T_{load} \Omega_{mot}}{J_{mot} + J_{load}} \]

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Type</td>
<td>Transistor Inverter</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Toshiba</td>
</tr>
<tr>
<td>Model No.</td>
<td>VF10P-2020B0</td>
</tr>
<tr>
<td>Number of Phases</td>
<td>Three</td>
</tr>
<tr>
<td>Rated kVA</td>
<td>2 kVA</td>
</tr>
<tr>
<td>Nominal Input Line Voltage</td>
<td>230 vac</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>6 to 60 Hz</td>
</tr>
<tr>
<td>Rated Output Current</td>
<td>7 amps</td>
</tr>
<tr>
<td>Control System</td>
<td>Sinusoidal wave PWM control</td>
</tr>
<tr>
<td>Voltage/Frequency Ratio</td>
<td>Variable</td>
</tr>
</tbody>
</table>

### DRIVE MOTOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Machine Type</td>
<td>AC Induction Machine</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Baldor Electric Company</td>
</tr>
<tr>
<td>Model No.</td>
<td>A36B05-107</td>
</tr>
<tr>
<td>Frame</td>
<td>182TC 623M</td>
</tr>
<tr>
<td>Number of Phases</td>
<td>Three</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>Four</td>
</tr>
<tr>
<td>Rated Power</td>
<td>3 hp</td>
</tr>
<tr>
<td>Rated Line-to-Line Voltage</td>
<td>230 vac</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Rated Stator Current</td>
<td>8.6 amps</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>1725 rpm</td>
</tr>
<tr>
<td>Insulation</td>
<td>Class B</td>
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### Permanent Magnet Alternator

<table>
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<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Type</td>
<td>Permanent Magnet Alternator</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>World Power Technologies, Inc.</td>
</tr>
<tr>
<td>Model No.</td>
<td>Whisper 600HV</td>
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<tr>
<td>Number of Phases</td>
<td>Three</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>10</td>
</tr>
<tr>
<td>Winding Configuration</td>
<td>Y-connected, 12 leads</td>
</tr>
<tr>
<td>Rated Power</td>
<td>600 watts</td>
</tr>
<tr>
<td>Rated Line-to-Line Voltage</td>
<td>280 vac</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>83.3 Hz</td>
</tr>
<tr>
<td>Rated Current</td>
<td>2.2 amps</td>
</tr>
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### LOAD MOTOR

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

### DYNAMOMETER

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

\[ L_1 := \sqrt{\frac{V^2}{I} - R_1^2} \frac{1}{2\pi f} \]

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:

\[ L_1 = \frac{\sqrt{\frac{E_a^2}{I} - \left( \frac{R_{load}}{R_a} \right)^2}}{2\pi f} \]

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 ohmeter 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.

<table>
<thead>
<tr>
<th>Slip</th>
<th>Current (Amps)</th>
<th>Power (Watts)</th>
<th>Slip</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.031</td>
<td>0.429</td>
<td>35</td>
<td>0.032</td>
<td>0.13</td>
</tr>
<tr>
<td>0.076</td>
<td>0.75</td>
<td>64</td>
<td>0.076</td>
<td>0.20</td>
</tr>
<tr>
<td>0.114</td>
<td>0.95</td>
<td>83</td>
<td>0.151</td>
<td>0.26</td>
</tr>
<tr>
<td>0.157</td>
<td>1.079</td>
<td>95</td>
<td>0.246</td>
<td>0.28</td>
</tr>
<tr>
<td>0.197</td>
<td>1.23</td>
<td>109</td>
<td>0.264</td>
<td>0.27</td>
</tr>
<tr>
<td>0.267</td>
<td>1.429</td>
<td>123</td>
<td>0.354</td>
<td>0.27</td>
</tr>
<tr>
<td>0.326</td>
<td>1.7</td>
<td>132</td>
<td>0.536</td>
<td>0.24</td>
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<tr>
<td>0.426</td>
<td>1.83</td>
<td>139</td>
<td>0.726</td>
<td>0.21</td>
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<tr>
<td>0.564</td>
<td>2</td>
<td>144</td>
<td>1.000</td>
<td>0.26</td>
</tr>
<tr>
<td>0.709</td>
<td>2.1</td>
<td>146</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.754</td>
<td>2.2</td>
<td>147</td>
<td></td>
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<tr>
<td>1</td>
<td>2.3</td>
<td>150</td>
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Applied Voltage = 104 VAC

<table>
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<tr>
<th>Slip</th>
<th>Current (Amps)</th>
<th>Power (Watts)</th>
<th>Slip</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>0.6</td>
<td>38.4</td>
<td>0.009</td>
<td>0.13</td>
</tr>
<tr>
<td>0.039</td>
<td>0.652</td>
<td>120</td>
<td>0.023</td>
<td>0.22</td>
</tr>
<tr>
<td>0.091</td>
<td>1.06</td>
<td>177</td>
<td>0.086</td>
<td>0.79</td>
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<tr>
<td>0.111</td>
<td>1.455</td>
<td>233</td>
<td>0.094</td>
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<tr>
<td>0.137</td>
<td>1.69</td>
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<tr>
<td>0.171</td>
<td>1.869</td>
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<td>0.214</td>
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<td>0.264</td>
<td>2.46</td>
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<td>0.333</td>
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<td>0.299</td>
<td>1.15</td>
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<tr>
<td>0.414</td>
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<tr>
<td>1</td>
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<td>0.367</td>
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<td></td>
<td></td>
<td></td>
<td>1.000</td>
<td>0.85</td>
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Applied Voltage = 209.5 VAC

<table>
<thead>
<tr>
<th>Slip</th>
<th>Current (Amps)</th>
<th>Power (Watts)</th>
<th>Slip</th>
<th>Torque (Nm)</th>
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</thead>
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<tr>
<td>0.003</td>
<td>1.35</td>
<td>91</td>
<td>0.003</td>
<td>0.16</td>
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<td>0.011</td>
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<td>0.041</td>
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<td>0.056</td>
<td>1.93</td>
<td>580</td>
<td>0.054</td>
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<td>0.083</td>
<td>2.38</td>
<td>790</td>
<td>0.067</td>
<td>2.80</td>
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<tr>
<td></td>
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<td></td>
<td>0.070</td>
<td>2.94</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.077</td>
<td>3.08</td>
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APPENDIX F: Detailed Results for Test 4 (Dynamic Line-Connected Induction Motor)
LINE CONNECTED MOTOR START-UP TEST

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  Line-to-line voltage 106 volt
9-Speed
10-Power
11-Frequency

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

Data matrix: \( M := \text{READPRN}(\text{line}_4) \)

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

Maximum time: \( T_{\text{max}} := M_{N-1,0} \text{ sec} \quad T_{\text{max}} = 2.848 \text{ sec} \)

\( i = 0 .. N - 1 \)

Time: \( t_i := M_{i,0} \text{ sec} \quad R_1 = 5.8 \text{- ohm} \quad P_m = 2 \)

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

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

Load torque: \( T_{\text{load},i} := M_{i,7} \text{- Nm} \quad \) Instantaneous power to motor: \( P_i := M_{i,9} \text{- watt} \)

Motor RPM: \( \text{Speed}_i := M_{i,8} \text{ RPM} \quad \) Alternator output frequency: \( f_i := 60 \text{- Hz} \)

Capacitance: \( \text{Cap}_1 = 72 \mu F \quad \) Voltages across capacitor: \( U_{\text{cap}A_i} := \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_1} \)

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

MOTOR START-UP
MOTOR START-UP
MOTOR START-UP
LINE CONNECTED MOTOR START-UP TEST

RPM=60-Hz·sec⁻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-03.dat file in NOLOAD directory.

Data matrix: \( M := \text{READPRN(line_03)} \)

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

Maximum time: \( T_{\text{max}} = M_{N} - 1.0 \cdot \text{sec} \quad T_{\text{max}} = 3.798 \cdot \text{sec} \)

\( i = 0..N - 1 \)

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

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: \( T_{load_i} := M_{i,7} \cdot \text{Nm} \quad \text{Instantaneous power to motor:} \quad P_i := M_{i,8} \cdot \text{watt} \)

Motor RPM: \( \text{Speed}_i := M_{i,9} \cdot \text{RPM} \quad \text{Alternator output frequency:} \quad f_i := 60 \cdot \text{Hz} \)

Capacitance: \( C_{api} := 72 \cdot \mu \text{F} \quad \text{Voltages across capacitor:} \quad U_{\text{cap}A_i} = \frac{1}{2 \cdot \pi \cdot f_i \cdot C_{api}} \)

Electromagnetic torque: \( T_{\text{em}_i} = \frac{P_i - R_1 \cdot \left( I_{A_i} \right)^2 + \left( I_{B_i} \right)^2 + \left( I_{C_i} \right)^2 \right]^{1/2}}{2 \cdot \pi \cdot f_i} \quad p_m \)
MOTOR START-UP
MOTOR START-UP
LINE CONNECTED MOTOR START-UP TEST

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

Line-to-line voltage 79 volt

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

Data matrix: \( M := \text{READPRN}(	ext{line}_01) \)

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

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

Time: \( t_i := M_{i,0} \cdot \text{sec} \quad R := 5.8 \cdot \text{ohm} \quad p_m := 2 \)

Instantaneous currents: \( I_A := M_{i,1} \cdot \text{amp} \quad I_B := M_{i,2} \cdot \text{amp} \quad I_C := M_{i,3} \cdot \text{amp} \)

Instantaneous line-to-line voltages: \( U_{AB} := M_{i,4} \cdot \text{volt} \quad U_{BC} := M_{i,5} \cdot \text{volt} \quad U_{CA} := M_{i,6} \cdot \text{volt} \)

Load torque: \( T_{\text{load}} := M_{i,7} \cdot \text{Nm} \quad \text{Instantaneous power to motor:} \quad P_i := M_{i,8} \cdot \text{watt} \)

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

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

Electromagnetic torque: \( T_{\text{em}i} := \frac{P_i - R_1 \left[ (I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i \cdot p_m} \)
MOTOR START-UP
MOTOR START-UP
APPENDIX G: Detailed Results for Test 5 (Steady-State Alternator / Induction Motor System)
### No-Load Test

<table>
<thead>
<tr>
<th>Freq</th>
<th>Model</th>
<th>Test</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>0.86</td>
<td>0.87</td>
<td>-0.00925</td>
</tr>
<tr>
<td>35</td>
<td>0.93</td>
<td>0.92</td>
<td>0.324675</td>
</tr>
<tr>
<td>40</td>
<td>0.94</td>
<td>0.95</td>
<td>-0.02239</td>
</tr>
<tr>
<td>46</td>
<td>0.96</td>
<td>0.98</td>
<td>-1.7418</td>
</tr>
<tr>
<td>61</td>
<td>0.99</td>
<td>1.00</td>
<td>0.69323</td>
</tr>
<tr>
<td>75</td>
<td>1.03</td>
<td>1.02</td>
<td>0.29269</td>
</tr>
</tbody>
</table>

**RMS Error** = 1.074355

<table>
<thead>
<tr>
<th>Freq</th>
<th>Model</th>
<th>Test</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>65.6</td>
<td>70.3</td>
<td>-6.6145</td>
</tr>
<tr>
<td>35</td>
<td>95.7</td>
<td>98.5</td>
<td>-2.8731</td>
</tr>
<tr>
<td>40</td>
<td>110.9</td>
<td>115.1</td>
<td>-3.6371</td>
</tr>
<tr>
<td>46</td>
<td>128.3</td>
<td>132.7</td>
<td>-3.3286</td>
</tr>
<tr>
<td>61</td>
<td>172.8</td>
<td>178.0</td>
<td>-2.8907</td>
</tr>
<tr>
<td>75</td>
<td>209.7</td>
<td>219.8</td>
<td>-4.61101</td>
</tr>
</tbody>
</table>

**RMS Error** = 4.216482
Locked-Rotor Test

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Model</th>
<th>Test</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>1.20</td>
<td>1.25</td>
<td>-4.0962</td>
</tr>
<tr>
<td>25</td>
<td>1.31</td>
<td>1.35</td>
<td>-3.04606</td>
</tr>
<tr>
<td>34</td>
<td>1.55</td>
<td>1.61</td>
<td>-3.48259</td>
</tr>
<tr>
<td>44</td>
<td>1.74</td>
<td>1.81</td>
<td>-3.60111</td>
</tr>
</tbody>
</table>

RMS Error = 3.551477

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Model</th>
<th>Test</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>19.8</td>
<td>22.9</td>
<td>-13.6245</td>
</tr>
<tr>
<td>25</td>
<td>22.1</td>
<td>25.8</td>
<td>-14.1667</td>
</tr>
<tr>
<td>34</td>
<td>28.7</td>
<td>33.2</td>
<td>-13.5301</td>
</tr>
<tr>
<td>44</td>
<td>35.8</td>
<td>41.2</td>
<td>-13.0437</td>
</tr>
</tbody>
</table>

RMS Error = 13.59708

Graphs showing current and voltage data across different frequencies.
APPENDIX H: Detailed Results for Test 6 (Dynamic Alternator / Induction Motor System)
1. MOTOR NO LOAD START-UP TEST

(capacitor was in the circuit during whole test)

RPM = 60 Hz \cdot \text{sec} \cdot \text{min}^{-1} \quad \text{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 n135hz.dat file in NOLOAD directory.

Data matrix: \( M := \text{READPRN(n135hz)} \)

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

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

\( i := 0 \ldots N - 1 \)

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

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

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

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

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

MOTOR START-UP
MOTOR START-UP
MOTOR START-UP
MOTOR START-UP

ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE
1. MOTOR NO LOAD START-UP TEST
(capacitor was in the circuit during whole test)

RPM = 60 \cdot Hz \cdot sec^{-1}
Nm = newton \cdot 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 n45hz.dat file in NOLOAD directory.

Data matrix: $M := \text{READPRN}(n45hz)$

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

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

Time: $t_i := M_{i,0} \cdot \text{sec}$

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: $T_{\text{load}} := M_{i,7} \cdot \text{Nm}$

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: $C_i := 72 \cdot \mu F$

Voltages across capacitor: $U_{\text{capA}i} := \frac{1}{1A_i} \cdot \frac{1}{2 \cdot \pi f_i C_i}$

 Electromagnetic torque: $T_{\text{em}} := \frac{P_i - R \cdot \text{I}}{2 \cdot \pi f_i}$

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

MOTOR START-UP
CURRENT

LINE-TO-LINE VOLTAGE

VOLTAGE ACROSS CAPACITOR

MOTOR START-UP
MOTOR START-UP
ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

MOTOR START-UP
1. MOTOR NO LOAD START-UP TEST

(capacitor was in the circuit during whole test)

RPM = 60 Hz sec⁻¹
Nm = newton·m

1-Time
2-I_A
3-I_B
4-I_C
5-V_A-B
6-V_B-C
7-V_C-A
8-Torque
9-Speed
10-Power
11-Frequency

Test data are stored in the n155hz.dat file in NOLOAD directory.

Data matrix: M := READPRN(n155hz)

Number of points: N := rows(M)×0.95 N = 2.28×10^3

Maximum time:  T_{max} := M_{N-1}×0.05 sec T_{max} = 3.798 sec

i = 0..N - 1

Time: t_i := M_i,0 sec
R_1 := 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_{A_B_i} := M_i,4 volt  U_{B_C_i} := M_i,5 volt  U_{C_A_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
Alternator output frequency: f_i := M_i,10 Hz

Capacitance:  Cap_i := 72 μF
Voltages across capacitor: U_{capA_i} := I_{A_i} \frac{1}{2×π×f_i×Cap_i}

Electromagnetic torque: T_{cm_i} := \frac{P_i - R_1 \left[ (I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2×π×f_i×p_m} \quad p_m

Alternator torque:  T_{alt_i} := \frac{P_i + R_a \left[ (I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2×π×f_i×p_{alt}}

MOTOR START-UP
MOTOR START-UP
MOTOR START-UP
ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

MOTOR START-UP
1. MOTOR NO LOAD START-UP TEST (65 Hz.)
(capacitor was in the circuit during whole test)

RPM = 60 Hz·sec·min⁻¹  INPUT CHANNEL MAP
Nm = newton·m

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

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

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

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

$i := 0..N - 1$

Time: $t_i := M_{i,0} \cdot \text{sec}$

Instantaneous currents: $I_{A1} := M_{i,1} \cdot \text{amp}$, $I_{B1} := M_{i,2} \cdot \text{amp}$, $I_{C1} := M_{i,3} \cdot \text{amp}$

Instantaneous line-to-line voltages: $U_{AB1} := M_{i,4} \cdot \text{volt}$, $U_{BC1} := M_{i,5} \cdot \text{volt}$, $U_{CA1} := M_{i,6} \cdot \text{volt}$

Load torque: $T_{\text{load1}} := M_{i,7} \cdot \text{Nm}$

Instantaneous power to motor: $P_i := M_{i,8} \cdot \text{watt}$

Motor RPM: $\text{Speed}_i := M_{i,9} \cdot \text{RPM}$

Alternator output frequency: $f_i := M_{i,10} \cdot \text{Hz}$

Capacitance: $C_{ap1} := 72 \cdot \mu\text{F}$

Voltages across capacitor: $U_{\text{capA1}} := I_{A1} \cdot \frac{1}{2\cdot\pi f_i \cdot C_{ap1}}$

Electromagnetic torque: $T_{\text{em1}} := \frac{P_i - R_a \cdot \left( I_{A1}^2 + (I_{B1})^2 + (I_{C1})^2 \right)}{2\cdot\pi f_i \cdot P_m}$

Alternator torque: $T_{\text{alt1}} := \frac{P_i + R_a \cdot \left( I_{A1}^2 + (I_{B1})^2 + (I_{C1})^2 \right)}{2\cdot\pi f_i \cdot P_{\text{alt}}}$

MOTOR START-UP
CURRENT

LINE-TO-LINE VOLTAGE

VOLTAGE ACROSS CAPACITOR

MOTOR START-UP
MOTOR START-UP
ELECTROMAGNETIC TORQUE

TIME (sec)

TORQUE (Nm)

0 0.5 1 1.5 2 2.5 3 3.5

-1 0 1 2 3

ALTERNATOR TORQUE

TIME (sec)

TORQUE (Nm)

0 0.5 1 1.5 2 2.5 3 3.5

-5 0 5 10 15 20

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

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-01.dat file in NOLOAD directory.

Data matrix: \( M := \text{READPRN}(\text{test}_01) \)

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

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

Time: \( t_i := M_{i,0} \cdot \text{sec} \)

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: \( T_{\text{load}_i} := M_{i,7} \cdot \text{Nm} \)

Motor RPM: \( \text{Speed}_i := M_{i,8} \cdot \text{RPM} \cdot 0.8262 \)

Alternator output frequency: \( f_i := M_{i,9} \cdot \text{Hz} \)

Capacitance: \( \text{Cap}_i := \begin{cases} 1, & (t_i > 1.05 \cdot \text{sec}) \land (t_i < 3 \cdot \text{sec}) \\ 72 \cdot \mu\text{F} \cdot 10^{10} \cdot \mu\text{F} & \end{cases} \quad U_{\text{cap}_A_i} := \frac{1}{2 \cdot \pi \cdot f_i \cdot \text{Cap}_i} \)

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

Alternator torque: \( T_{\text{alt}_i} := \frac{P_i + R_a \left[ (I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi \cdot f_i} \cdot \text{P}_\text{alt} \)
MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

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

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-Speed
9-Torque
10-Power
11-Frequency

Test data are stored in the test02.dat file in NOLOAD directory.

Data matrix: \( M := \text{READPFN(test}_02) \)

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

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

\( i := 0 \ldots N-1 \)

Time: \( t_i := M_{i,0} \cdot \text{sec} \)
\( R_1 := 5.8 \cdot \text{ohm} \quad P_m := 2 \quad R_a := 36 \cdot \text{ohm} \quad P_{\text{alt}} := 5 \)

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: \( T_{\text{load}} := M_{i,7} \cdot \text{Nm} \quad \text{Instantaneous power to motor: } \quad P_i := M_{i,8} \cdot \text{watt} \)

Motor RPM: \( \text{Speed}_i := M_{i,9} \cdot \text{RPM} \cdot 0.8262 \quad \text{Alternator output frequency: } \quad f_i := M_{i,10} \cdot \text{Hz} \)

Capacitance: \( \text{Cap}_i := \frac{1}{\frac{1}{2} \cdot \left( f_i \cdot 1.25 \cdot \text{sec} \cdot f_i \cdot 3 \cdot \text{sec} \right) \cdot 72 \cdot \mu \text{F} \cdot 10^{10} \cdot \mu \text{F}} \)

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

Alternator torque: \( T_{\text{alt}} := \frac{P_i + R_a \left[ (I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \cdot \pi f_i} \cdot P_{\text{alt}} \)
MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

- Motor electromagnetic torque
- Load torque

ALTERNATOR TORQUE

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

RPM = 60 Hz-section-1
Nm = newton-meter

- Time
- IA
- IB
- IC
- VAB
- VBC
- VCA
- Torque
- Speed
- Power
- Frequency

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

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

Number of points:  
\[
N := \text{rows}(M) - 0.95 \quad N = 2.28 \times 10^3
\]

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

\[
i := 0 \ldots N - 1
\]

Time:  
\[
t_i := M_{i, 0} \text{sec} \quad R_1 := 5.8 \text{ ohm} \quad P_m := 2 \quad R_a := 36 \text{ ohm} \quad p_{alt} := 5
\]

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

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

Load torque:  
\[
T_{load_i} := M_{i, 7} \text{Nm}
\]

Instantaneous power to motor:  
\[
P_i := M_{i, 8} \text{watt}
\]

Motor RPM:  
\[
\text{Speed}_i := M_{i, 9} \text{RPM} \cdot 0.8262
\]

Alternator output frequency:  
\[
f_i := M_{i, 10} \text{Hz}
\]

Capacitance:  
\[
C_{Ap_i} := \begin{cases}
\frac{1}{(i > 1.4 \text{ sec})} \cdot (i < 2.9 \text{ sec}), & 72 \mu F, 10^{10} \mu F
\end{cases}
\]

\[
U_{capA_i} := I_{A_i} \frac{1}{2 \pi f_i C_{Ap_i}}
\]

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

Alternator torque:  
\[
T_{alt_i} := \frac{P_i + R_a \left[ (I_{A_i})^2 + (I_{B_i})^2 + (I_{C_i})^2 \right]}{2 \pi f_i P_{alt}}
\]
LOADSTO3.MCD

CURRENT

LINE-TO-LINE VOLTAGE

VOLTAGE ACROSS CAPACITOR

MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

0 0.5 1 1.5 2 2.5 3 3.5

Time (sec)

Motor electromagnetic torque
Load torque

ALTERNATOR TORQUE

0 0.5 1 1.5 2 2.5 3 3.5

Time (sec)

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

RPM = 60 Hz sec⁻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: \[ M = \text{READPRN(test	extunderscore 04)} \]

Number of points: \[ N = \text{rows(M)} \times 0.95 \quad N = \text{3.42} \times 10^3 \]

Maximum time: \[ T_{\text{max}} = M_{N-1} \times 0.8 \text{ sec} \]

\[ i = 0..N-1 \]

Time: \[ t_i = M_{i, 0} \text{ sec} \]

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

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

Load torque: \[ T_{\text{load}_i} = M_{i, 7} \text{ Nm} \]

Motor RPM: \[ \text{Speed}_i = M_{i, 8} \text{ RPM} \times 0.8262 \]

Alternator output frequency: \[ f_i = M_{i, 10} \text{ Hz} \]

Capacitance: \[ C_{A_i} = \begin{cases} 10^{-10} \text{ F} & \text{if } (t_i > 1.5 \text{ sec}) \text{ and } (t_i < 5 \text{ sec}) \\ 72 \text{ pF} & \text{otherwise} \end{cases} \]

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

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

MOTOR START-UP
MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

MOTOR START-UP
APPENDIX I: Validation Results for Dynamic Tests of Alternator / Induction Motor System
2. COMPARISON OF TEST AND MODELING RESULTS

Model 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

Data matrix: 

\[
B := \text{READPRN(noload01)}
\]

Number of rows: 

\[
L := \text{rows}(B) \quad L = 1.278\times10^3
\]

Maximum time: 

\[
T_{\text{max}} := B_{L-1,0}\ \text{sec} \quad T_{\text{max}} = 2\ \text{sec}
\]

\[
j := 0..L - 1
\]

\[
t_{\text{model}} := B_{j,0}\ \text{sec}
\]

\[
f_{\text{model}} := B_{j,1}\ \text{Hz}
\]

\[
\text{Speed}_{\text{model}} := B_{j,2}\ \text{RPM}
\]

\[
I_{A,\text{model}} := B_{j,3}\ \text{amp}
\]

\[
U_{\text{Amot, model}} := B_{j,4}\ \text{volt}
\]

\[
U_{Aalt, model} := B_{j,5}\ \text{volt}
\]

\[
T_{\text{alt, model}} := B_{j,6}\ \text{Nm}
\]

\[
T_{\text{mot, model}} := B_{j,7}\ \text{Nm}
\]

\[
P_{\text{model}} := B_{j,8}\ \text{kW}
\]

\[
U_{\text{capA, model}} := B_{j,9}\ \text{volt}
\]

MOTOR START-UP
CURRENT

- Test
- Model

ALTERNATOR PHASE VOLTAGE

- Test
- Model

MOTOR START-UP
VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

- Test
- Model

ALTERNATOR ELECTROMAGNETIC TORQUE

- Test
- Model

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

Data matrix: \( B \) := READPRN(noload02)

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

Maximum time: \( T_{\text{max}} := B_{L-1,6} \cdot \text{sec} \)
\( T_{\text{max}} = 1.0 \text{ sec} \)

\( j := 0..L-1 \)

\( t_{\text{model}}_j := B_{j,0} \cdot \text{sec} \)
\( T_{\text{alt.model}}_j := B_{j,6} \cdot \text{Nm} \)
\( f_{\text{model}}_j := B_{j,1} \cdot \text{Hz} \)
\( T_{\text{mot.model}}_j := B_{j,7} \cdot \text{Nm} \)
\( \text{Speed}_{\text{model}}_j := B_{j,2} \cdot \text{RPM} \)
\( T_{\text{mot.model}}_j := B_{j,7} \cdot \text{Nm} \)
\( I_{\text{A.model}}_j := B_{j,5} \cdot \text{amp} \)
\( P_{\text{model}}_j := B_{j,8} \cdot \text{kW} \)
\( U_{\text{Amot.model}}_j := B_{j,4} \cdot \text{volt} \)
\( U_{\text{capA.model}}_j := B_{j,9} \cdot \text{volt} \)

U_{\text{Aalt.model}}_j := B_{j,5} \cdot \text{volt}
CURRENT

- Test
- Model

ALTERNATOR PHASE VOLTAGE

- Test
- Model

MOTOR START-UP
VOLTAGE ACROSS CAPACITOR

Test
Model

ALTERNATOR OUTPUT POWER

Test
Model

MOTOR START-UP
MOTOR START-UP

- Test
- Model

FREQUENCY

MOTOR RPM

TIME (sec)

TIME (sec)
MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR ELECTROMAGNETIC TORQUE

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

Data matrix: \[ B := \text{READPRN(noload03)} \]
Number of rows: \[ L := \text{rows}(B) \quad L = 863 \]
Maximum time: \[ T_{\text{max}} := B_{L-1,0}\, \text{sec} \quad T_{\text{max}} = 1\, \text{sec} \]

\[ j = 0 \ldots L - 1 \]

\[ t_{\text{model}} := B_{j,0}\, \text{sec} \quad T_{\text{alt.model}} := B_{j,6}\, \text{Nm} \]

\[ f_{\text{model}} := B_{j,1}\, \text{Hz} \quad T_{\text{mot.model}} := B_{j,7}\, \text{Nm} \]

\[ \text{Speed}_{\text{model}} := B_{j,2}\, \text{RPM} \quad P_{\text{model}} := B_{j,8}\, \text{kW} \]

\[ I_{\text{A.model}} := B_{j,3}\, \text{amp} \quad P_{\text{capA.model}} := B_{j,9}\, \text{volt} \]

\[ U_{\text{Amot.model}} := B_{j,4}\, \text{volt} \quad U_{\text{Aalt.model}} := B_{j,5}\, \text{volt} \]

MOTOR START-UP

55 Hz
MOTOR START-UP
VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

Test
Model

ALTERNATOR ELECTROMAGNETIC TORQUE

Test
Model

MOTOR START-UP
2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modedata\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

Data matrix: \( B := \text{READPRN(noload04)} \)
Number of rows: \( L := \text{rows}(B) \quad L = 964 \)
Maximum time: \( T_{\text{max}} := B_{L-1,0} \cdot \text{sec} \quad T_{\text{max}} = 1 \cdot \text{sec} \)

\( j = 0 \ldots L - 1 \)

\( t_{\text{model}} := B_{j,0} \cdot \text{sec} \)
\( f_{\text{model}} := B_{j,1} \cdot \text{Hz} \)
\( \text{Speed}_{\text{model}} := B_{j,2} \cdot \text{RPM} \)
\( I_{\text{A.model}} := B_{j,3} \cdot \text{amp} \)
\( U_{\text{Amot.model}} := B_{j,4} \cdot \text{volt} \)
\( U_{\text{Aalt.model}} := B_{j,5} \cdot \text{volt} \)
\( T_{\text{alt.model}} := B_{j,6} \cdot \text{Nm} \)
\( T_{\text{mot.model}} := B_{j,7} \cdot \text{Nm} \)
\( P_{\text{model}} := B_{j,8} \cdot \text{kW} \)
\( U_{\text{capA.model}} := B_{j,9} \cdot \text{volt} \)

MOTOR START-UP
VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

MOTOR START-UP
MOTOR START-UP

FREQUENCY

MOTOR RPM

9/29/95
MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR ELECTROMAGNETIC TORQUE

MOTOR START-UP
2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\load01.dat.

<table>
<thead>
<tr>
<th>Time</th>
<th>Column 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternator frequency</td>
<td>Column 2</td>
</tr>
<tr>
<td>Motor RPM</td>
<td>Column 3</td>
</tr>
<tr>
<td>Stator current</td>
<td>Column 4</td>
</tr>
<tr>
<td>Motor input voltage</td>
<td>Column 5</td>
</tr>
<tr>
<td>Alternator output voltage</td>
<td>Column 6</td>
</tr>
<tr>
<td>Motor torque</td>
<td>Column 7</td>
</tr>
<tr>
<td>Alternator torque</td>
<td>Column 8</td>
</tr>
<tr>
<td>Motor input power</td>
<td>Column 9</td>
</tr>
<tr>
<td>Voltage across capacitors</td>
<td>Column 10</td>
</tr>
</tbody>
</table>

Data matrix: \[ B := \text{READPF3J}(\text{loadst01}) \]

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

Maximum time: \[ T_{\text{max}} = B_{L-1,0} \text{ sec} \quad T_{\text{max}} = 3 \text{ sec} \]

\[ j := 0 \ldots L - 1 \]

\[ t_{\text{model}} := B_{j,0} \text{ sec} \quad T_{\text{alt.model}} := B_{j,6} \text{ Nm} \]

\[ f_{\text{model}} := B_{j,1} \text{ Hz} \cdot 0.945 \quad T_{\text{mot.model}} := B_{j,7} \text{ Nm} \]

\[ \text{Speed}_{\text{model}} := B_{j,2} \text{ RPM} \quad P_{\text{model}} := B_{j,8} \text{ kW} \]

\[ I_{\text{A.model}} := B_{j,3} \text{ amp} \quad U_{\text{capA.model}} := B_{j,5} \text{ volt} \]

\[ U_{\text{Amot.model}} := B_{j,4} \text{ volt} \quad U_{\text{Aalt.model}} := B_{j,5} \text{ volt} \]

\[ \Delta T := 0.62 \text{ sec} \]

MOTOR START-UP
MOTOR START-UP
VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR ELECTROMAGNETIC TORQUE

MOTOR START-UP
2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\unload02.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

Data matrix: B := READPRN(loadst02)
Number of rows: L := rows(B) L = 2.355 \times 10^3
Maximum time: T_{\text{max}} := B_{L-1,0} \text{sec} \quad T_{\text{max}} = 2.5 \text{sec}

j := 0 . . . L - 1

t_{\text{model}}^j := B_{j,0} \text{sec}

f_{\text{model}}^j := B_{j,1} \text{Hz}

\text{Speed}_{\text{model}}^j := B_{j,2} \text{RPM}

I_{\text{A,model}}^j := B_{j,3} \text{amp}

U_{\text{Amot,model}}^j := B_{j,4} \text{volt}

U_{\text{Aalt,model}}^j := B_{j,5} \text{volt}

\Delta T := 0.8 \text{sec}

MOTOR START-UP
MOTOR START-UP
MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR ELECTROMAGNETIC TORQUE

MOTOR START-UP
2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\load04.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

Data matrix: \[ B := \text{READPRN} \text{ loadst03,} \]

Number of rows: \[ L := \text{rows} \text{ } B \]
\[ L = 2.185 \times 10^3 \]

Maximum time: \[ T_{\text{max}} = B_1 = 1 \text{ sec} \quad T_{\text{max}} = 3 \text{ sec} \]

\[ j = 0 \text{ to } L - 1 \]

\[ t_{\text{model}}_j := B_{j,0} \text{ sec} \]

\[ f_{\text{model}}_j := B_{j,1} \text{ Hz} \]

\[ \text{Speed}_{\text{model}}_j := B_{j,2} \text{ RPM} \]

\[ I_{\text{A.mode}}_j := B_{j,3} \text{ amp} \]

\[ U_{\text{Amot.mode}}_j := B_{j,4} \text{ volt} \]

\[ U_{\text{A.alt.mode}}_j := B_{j,5} \text{ volt} \]

\[ \Delta T := 0.88 \text{ sec} \]

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

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

\[ P_{\text{model}}_j := B_{j,8} \text{ kW} \]

\[ U_{\text{capA.mode}}_j := B_{j,9} \text{ volt} \]

MOTOR START-UP
MOTOR START-UP
VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

MOTOR START-UP
MOTOR START-UP
MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR ELECTROMAGNETIC TORQUE

MOTOR START-UP
2. COMPARISON OF TEST AND MODELING RESULTS

Modelling data are stored in the c:\myfiles\ice\dynamic\modeldata\no\load04.dat.

<table>
<thead>
<tr>
<th>Time</th>
<th>Alternator frequency</th>
<th>Motor RPM</th>
<th>Stator current</th>
<th>Motor input voltage</th>
<th>Alternator output voltage</th>
<th>Motor torque</th>
<th>Alternator torque</th>
<th>Motor input power</th>
<th>Voltage across capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>Column 2</td>
<td>Column 3</td>
<td>Column 4</td>
<td>Column 5</td>
<td>Column 6</td>
<td>Column 7</td>
<td>Column 8</td>
<td>Column 9</td>
<td>Column 10</td>
</tr>
</tbody>
</table>

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

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

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

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

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

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

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

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

MOTOR START-UP
MOTOR START-UP
VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

MOTOR START-UP
MOTOR START-UP

FREQUENCY

MOTOR RPM

Test

Model
MOTOR ELECTROMAGNETIC TORQUE

Test
Model

ALTERNATOR ELECTROMAGNETIC TORQUE

Test
Model

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\modeIdat\noload01.dat.

- Nm := newton\-m
- Data matrix: B := READPRN(noload01)
- Number of rows: L := rows(B)  
  \( L = 2.569 \times 10^3 \)
- Maximum time: \( T_{\text{max}} := B_{L-1,0} \text{ sec} \quad T_{\text{max}} = 5 \text{ sec} \)

\[
\begin{align*}
    i &:= 0 .. L - 1 \\
    t_i &:= B_{i,0} \text{ sec} \quad f_i := B_{i,1} \text{ Hz} \quad \text{Speed}_i := B_{i,2} \quad I_{A_i} := B_{i,3} \text{ amp} \quad U_{\text{Amot}_i} := B_{i,4} \text{ volt} \\
    U_{\text{Aalt}_i} &:= B_{i,5} \text{ volt} \quad T_{\text{alt}_i} := B_{i,6} \text{ Nm} \quad T_{\text{mot}_i} := B_{i,7} \text{ Nm} \quad P_i := B_{i,8} \text{ kW} \\
    T_{w_i} &:= B_{i,9} \text{ Nm} \quad T_{\text{load}_i} := B_{i,10} \text{ Nm} \quad V_i := B_{i,11} \text{ m/sec} \quad U_{\text{capA}_i} := B_{i,12} \text{ volt} \\
\end{align*}
\]

**WIND SPEED**

**CURRENT**

**MOTOR START-UP**
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

---

Motor
Load

Motor Start-Up
80HZ.MCD

Base case: 2. Constant Load

Data are stored in c:\matlab\icehodeldata\load01.dat.

N m := newton-m

Data matrix: B := READPRN(load01)

Number of rows: L := rows(B)  L = 26

Maximum time: T max := B L-1.0-sec  T max = 0.022-sec

\[
i := 0 \ldots L - 1
\]

\[
\begin{align*}
t_i & := B_{i,0} \text{ sec} \\
f_i & := B_{i,1} \text{ Hz} \\
\text{Speed}_i & := B_{i,2} \text{ } \\
\text{IA}_i & := B_{i,3} \text{ amp} \\
\text{U Amot}_i & := B_{i,4} \text{ volt} \\
\text{U Alt}_i & := B_{i,5} \text{ volt} \\
\text{T Alt}_i & := B_{i,6} \text{ Nm} \\
\text{T Mot}_i & := B_{i,7} \text{ Nm} \\
\text{P}_i & := B_{i,8} \text{ kW} \\
\text{T Wi}_i & := B_{i,10} \text{ Nm} \\
\text{T Load}_i & := B_{i,11} \text{ Nm} \\
\text{V}_i & := B_{i,12} \text{ m/sec} \\
\text{U CapA}_i & := B_{i,9} \text{ volt}
\end{align*}
\]

MOTOR START-UP
MOTOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

FREQUENCY

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR PHASE VOLTAGE

ALTERNATOR OUTPUT POWER

MOTOR RPM

ALTERNATOR TORQUE

MOTOR START-UP

---

Motor
Load

Alternator
Wind Rotor
Switched capacitor: 1. Constant Load

Data are stored in `c:\matlab\rice\modeldata\loadc01.dat`. 

\[ Nm := \text{newton-m} \]

\[
\begin{align*}
\text{Capacitance:} & \quad C := 200 \ \mu F \\
\text{Data matrix:} & \quad B := \text{READPRN(\text{loadc01})} \\
\text{Number of rows:} & \quad L := \text{rows}(B) \quad L = 801 \\
\text{Maximum time:} & \quad T_{\text{max}} := B_{L-1,0} \ \text{sec} \quad T_{\text{max}} = 0.5 \ \text{sec}
\end{align*}
\]

\[
i := 0 \ldots L - 1
\]

\[
\begin{align*}
t_i & := B_{i,0} \ \text{sec} \quad f_i := B_{i,1} \ \text{Hz} \quad \text{Speed}_i := B_{i,2} \quad I_{A_i} := B_{i,3} \ \text{amp} \quad U_{\text{Amot}_i} := B_{i,4} \ \text{volt} \\
U_{\text{Aalt}_i} & := B_{i,5} \ \text{volt} \quad T_{\text{alt}_i} := B_{i,6} \ \text{Nm} \quad T_{\text{mot}_i} := B_{i,7} \ \text{Nm} \quad P_i := B_{i,8} \ \text{kW} \\
T_{w_i} & := B_{i,10} \ \text{Nm} \quad T_{\text{load}_i} := B_{i,11} \ \text{Nm} \quad V_i := B_{i,12} \ \frac{m}{\text{sec}} \quad U_{\text{capA}_i} := B_{i,9} \ \text{volt}
\end{align*}
\]

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

\[
\begin{align*}
\text{WIND SPEED} \\
\text{SPEED (m/s)} & \quad 0 \quad 5 \quad 10 \\
\text{TIME (sec)} & \quad 0 \quad 0.2 \quad 0.4
\end{align*}
\]

\[
\begin{align*}
\text{CURRENT} \\
\text{CURRENT (A)} & \quad -200 \quad 0 \quad 200 \\
\text{TIME (sec)} & \quad 0 \quad 0.2 \quad 0.4
\end{align*}
\]

MOTOR START-UP
MOTOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR PHASE VOLTAGE

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

Motor

Load

Alternator

Wind Rotor

MOTOR START-UP
Switched capacitor: 2. Sinusoidal Load

Data are stored in c:\matlab\ice\modeldata\load-c01.dat. Nm := newton·m

Capacitance: C := 200 μF

Data matrix: B := READPRN(loadsi01)

Number of rows: L := rows(B) L := 799

Maximum time: T max := B L − 1; 0·sec  T max := 0.5·sec

\[ i := 0..L-1 \]
\[ t_i := B_{i,0} \cdot \text{sec} \quad f_i := B_{i,1} \cdot \text{Hz} \quad \text{Speed}_i := B_{i,2} \quad I_{A_i} := B_{i,3} \cdot \text{amp} \quad \text{U}_{\text{Amot}_i} := B_{i,4} \cdot \text{volt} \]
\[ \text{U}_{\text{Alt}_i} := B_{i,5} \cdot \text{volt} \quad \text{T}_{\text{Alt}_i} := B_{i,6} \cdot \text{Nm} \quad \text{T}_{\text{Mot}_i} := B_{i,7} \cdot \text{Nm} \quad P_i := B_{i,8} \cdot \text{kW} \]
\[ \text{T}_{\text{Wi}} := B_{i,10} \cdot \text{Nm} \quad \text{T}_{\text{Load}_i} := B_{i,11} \cdot \text{Nm} \quad V_i := B_{i,12} \cdot \text{m sec} \quad \text{U}_{\text{CapA}_i} := B_{i,9} \cdot \text{volt} \]

Capacitor is off when t>0.2 sec.

WIND SPEED

CURRENT

MOTOR START-UP
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

- Motor
- Load

- Alternator
- Wind Rotor

MOTOR START-UP
**80HZ.MCD**

**CLUTCH: 1. Constant Load**

Data are stored in `c:\matlab\ice\model\data\loadcl01.dat`.  
Nm := newton·m

Data matrix:  
\[ B := \text{READPRN(loadcl01)} \]

Number of rows:  
\[ L := \text{rows}(B) \quad L = 5.074 \times 10^3 \]

Maximum time:  
\[ T_{\text{max}} := B_{L-1,0} \text{sec} \quad T_{\text{max}} = 8 \text{sec} \]

\[ i := 0 \ldots L - 1 \]

\[ t_i := B_{i,0} \text{ sec} \quad f_i := B_{i,1} \text{ Hz} \quad \text{Speed}_i := B_{i,2} \quad I_{A_i} := B_{i,3} \text{ amp} \quad U_{\text{Amot}_i} := B_{i,4} \text{ volt} \]

\[ U_{\text{Aalt}_i} := B_{i,5} \text{ volt} \quad T_{\text{alt}_i} := B_{i,6} \text{ Nm} \quad T_{\text{mot}_i} := B_{i,7} \text{ Nm} \quad P_i := B_{i,8} \text{ kW} \]

\[ T_{\text{wi}} := B_{i,9} \text{ Nm} \quad T_{\text{load}_i} := B_{i,10} \text{ Nm} \quad V_i := B_{i,11} \frac{\text{m}}{\text{sec}} \quad U_{\text{capA}_i} := B_{i,9} \text{ volt} \]

**WIND SPEED**

**CURRENT**

**MOTOR START-UP**
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

--- Motor
--- Load

--- Alternator
--- Wind Rotor

MOTOR START-UP
**CLUTCH: 2. Sinusoidal Load**

Data are stored in `c:\matlab\ice\modeldata\loa-cl01.dat`. 

Nm := newton-m

Data matrix: `B := READPRN(loadsincl01)`

Number of rows: `L := rows(B) L = 5.104·10^3`

Maximum time: `T_{max} := B_{L-1,0}·sec T_{max} = 8·sec`

\[ i := 0..L-1 \]

\[ t_i := B_{i,0}·sec f_i := B_{i,1}·Hz \]

\[ \text{Speed}_i := B_{i,2} \]

\[ I_{A_i} := B_{i,3}·amp \]

\[ U_{Amot_i} := B_{i,4}·volt \]

\[ U_{Aalt_i} := B_{i,5}·volt \]

\[ T_{alt_i} := B_{i,6}·Nm \]

\[ T_{mot_i} := B_{i,7}·Nm \]

\[ P_i := B_{i,8}·kW \]

\[ T_{wi} := B_{i,10}·Nm \]

\[ T_{loadi} := B_{i,11}·Nm \]

\[ V_i := B_{i,12}·\frac{m}{sec} \]

\[ U_{capAi} := B_{i,9}·volt \]

---

**MOTOR START-UP**

![Wind Speed](image1)

![Current](image2)
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

- 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 := READPRN(noload02)

Number of rows: 
L := rows(B) 
L = 990

Maximum time: 
T max := B L - 1.0 sec 
T max := 2 sec

i := 0..L - 1

\[ t_i := B_{i,0} \text{ sec} \]
\[ f_i := B_{i,1} \text{ Hz} \]
\[ \text{Speed}_i := B_{i,2} \]
\[ I_{A_i} := B_{i,3} \text{ amp} \]
\[ I_{Amot_i} := B_{i,4} \text{ volt} \]
\[ U_{A\text{lt}_i} := B_{i,5} \text{ volt} \]
\[ T_{\text{alt}_i} := B_{i,6} \text{ Nm} \]
\[ T_{\text{mot}_i} := B_{i,7} \text{ Nm} \]
\[ P_i := B_{i,8} \text{ kW} \]
\[ T_{\text{wi}} := B_{i,10} \text{ Nm} \]
\[ T_{\text{load}_i} := B_{i,11} \text{ Nm} \]
\[ V_i := B_{i,12} \frac{m}{\text{sec}} \]
\[ U_{\text{capA}_i} := B_{i,9} \text{ volt} \]

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

WIND SPEED

CURRENT

MOTOR START-UP
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

Motor
Load
Alternator
Wind Rotor

MOTOR START-UP
Basecase: 2. Constant Load

Data are stored in c:\matlab\ice\modeldata\load0L.dat.  

\[ Nm = \text{newton-m} \]

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

\[ B := \text{READPRN(load02)} \]

Number of rows:  
\[ L := \text{rows}(B) \]  
\[ L = 26 \]

Maximum time:  
\[ T_{\text{max}} = B_{L - 1,0} \text{sec} \]  
\[ T_{\text{max}} = 0.05 \text{sec} \]

\[ t_i := 0..L - 1 \]
\[ t_i := B_{i,0} \text{sec} \]  
\[ f_i := B_{i,1} \text{Hz} \]  
\[ \text{Speed}_i := B_{i,2} \]  
\[ I_{A_i} := B_{i,3} \text{amp} \]  
\[ U_{\text{Amot}_i} := B_{i,4} \text{volt} \]
\[ U_{\text{Alt}_i} := B_{i,5} \text{volt} \]  
\[ T_{\text{Alt}_i} := B_{i,6} \text{Nm} \]  
\[ T_{\text{mot}_i} := B_{i,7} \text{Nm} \]  
\[ P_i := B_{i,8} \text{kW} \]
\[ T_{\text{w}_i} := B_{i,9} \text{Nm} \]  
\[ T_{\text{load}_i} := B_{i,10} \text{Nm} \]  
\[ V_i := B_{i,11} \frac{\text{m}}{\text{sec}} \]  
\[ U_{\text{cap}_A_i} := B_{i,12} \text{volt} \]
\[ \text{Speed}_2 := \text{Speed} \]  
\[ t_2 := t \]  
\[ N_2 := L \]

\[ WIND SPEED \]
\[ \begin{array}{c|c|c|c}
   \text{SPEED (m/s)} & 0 & 5 & 10 \\
   \text{TIME (sec)} & 0 & 0.02 & 0.04 \\
\end{array} \]

\[ CURRENT \]
\[ \begin{array}{c|c|c|c}
   \text{CURRENT (A)} & -50 & 0 & 50 \\
   \text{TIME (sec)} & 0 & 0.02 & 0.04 \\
\end{array} \]

MOTOR START-UP
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

---

- Motor
- Load
- Alternator
- Wind Rotor

MOTOR START-UP
Switched capacitor: 1. Constant Load

Data are stored in c:\matlab\ice\modeldata\loadc01.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
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: \( C := 1500 \mu\text{F} \)

Data matrix: \( B := \text{READPRN(loadc02)} \)

Number of rows: \( L := \text{rows}(B) \quad L = 629 \)

Maximum time: \( T_{\text{max}} := B_L \quad 1.0 \text{ sec} \quad T_{\text{max}} = 1.0 \text{ sec} \)

\[
\begin{align*}
i &:= 0 \ldots L - 1 \\
t_i &:= B_{1,0} \text{ sec} \\
f_i &:= B_{1,1} \text{ Hz} \\
\text{Speed}_i &:= B_{1,2} \\
I_{A_i} &:= B_{1,3} \text{ amp} \\
U_{\text{Amot}_i} &:= B_{1,4} \text{ volt} \\
U_{\text{All}_i} &:= B_{1,5} \text{ volt} \\
T_{\text{alt}_i} &:= B_{1,6} \text{ Nm} \\
T_{\text{mot}_i} &:= B_{1,7} \text{ Nm} \\
P_i &:= B_{1,8} \text{ kW} \\
T_{\text{wi}_i} &:= B_{1,10} \text{ Nm} \\
T_{\text{load}_i} &:= B_{1,11} \text{ Nm} \\
V_i &:= B_{1,12} \frac{\text{m}}{\text{sec}} \\
U_{\text{capA}_i} &:= B_{1,9} \text{ volt} \\
\text{Speed}_3 &:= \text{Speed} \\
t_3 &:= t \\
N_3 &:= L
\end{align*}
\]

Capacitor is off when \( t > 0.2 \) sec.

![Wind Speed Diagram](image1)

![Current Diagram](image2)
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

- Motor
- Load
- Alternator
- Wind Rotor

MOTOR START-UP
Switched capacitor: 2. Sinusoidal Load

Data are stored in c:\matlab\ice\modeldat\load-e01.dat.

\[ N_m := \text{newton-m} \]

Capacitance: \[ C := 1500-\mu\text{F} \]

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

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

Maximum time: \[ T_{\text{max}} := B_{\text{L-1.0}\text{sec}} \]
\[ T_{\text{max}} = 1\text{sec} \]

\[ i := 0..L-1 \]

\[ t_i := B_{i,0}\text{sec} \]
\[ f_i := B_{i,1}\text{Hz} \]
\[ \text{Speed}_i := B_{i,2} \]
\[ I_{A_i} := B_{i,3}\text{amp} \]
\[ U_{\text{Amot}_i} := B_{i,4}\text{volt} \]
\[ U_{\text{Aalt}_i} := B_{i,5}\text{volt} \]
\[ T_{\text{alt}_i} := B_{i,6}\text{Nm} \]
\[ T_{\text{mot}_i} := B_{i,7}\text{Nm} \]
\[ P_i := B_{i,8}\text{kW} \]
\[ T_{\text{w}_{i}} := B_{i,10}\text{Nm} \]
\[ T_{\text{load}_{i}} := B_{i,11}\text{Nm} \]
\[ V_i := B_{i,12}\frac{\text{m}}{\text{sec}} \]
\[ U_{\text{capA_{i}}} := B_{i,9}\text{volt} \]

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

Capacitor is off when \( t > 0.2\text{ sec} \).
MOTOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

FREQUENCY

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR PHASE VOLTAGE

ALTERNATOR OUTPUT POWER

MOTOR RPM

ALTERNATOR TORQUE

---
- Motor
- Load

MOTOR START-UP

---
- Alternator
- Wind Rotor
CLUTCH: 1. Constant Load

Data are stored in c:\matlab\ice\modeldata\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: \( B := \text{READPRN(loadcl02)} \)

Number of rows: \( L := \text{rows}(B) \quad L = 1.011 \times 10^3 \)

Maximum time: \( T_{\text{max}} := B_{L-1,0} \text{sec} \quad T_{\text{max}} = 2 \text{-sec} \)

\[ i := 0 \ldots L - 1 \]
\[ t_i := B_{i,0} \text{sec} \quad f_i := B_{i,1} \text{Hz} \quad \text{Speed}_i := B_{i,2} \quad I_{A_i} := B_{i,3} \text{amp} \quad U_{A_{mot,i}} := B_{i,4} \text{volt} \]
\[ U_{A_{alt,i}} := B_{i,5} \text{volt} \quad T_{alt_i} := B_{i,6} \text{Nm} \quad T_{\text{mot}_i} := B_{i,7} \text{Nm} \quad P_i := B_{i,8} \text{kW} \]
\[ T_{W_i} := B_{i,10} \text{Nm} \quad T_{\text{load}_i} := B_{i,11} \text{Nm} \quad V_i := B_{i,12} \text{m/sec} \quad U_{\text{cap}A_i} := B_{i,9} \text{volt} \]

\[ \text{Speed}_5 := \text{Speed} \quad t_5 := t \quad N_5 := L \]
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

Motor
Load
Alternator
Wind Rotor

MOTOR START-UP
CLUTCH: 2. Sinusoidal Load

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

Nm := newton-m

Data matrix: B := READPRN(loadsincl02)

Number of rows: L := rows(B)  \[ L = 1.011 \times 10^3 \]

Maximum time: \[ T_{\text{max}} = B_{L-1} \cdot \text{sec} \quad T_{\text{max}} = 2 \cdot \text{sec} \]

\[ i := 0..L-1 \]
\[ t_i := B_{i,0} \cdot \text{sec} \]
\[ f_i := B_{i,1} \cdot \text{Hz} \]
\[ \text{Speed}_i := B_{i,2} \]
\[ I_{A_i} := B_{i,3} \cdot \text{amp} \]
\[ U_{\text{Amot}_i} := B_{i,4} \cdot \text{volt} \]
\[ U_{\text{Alt}_{alt_i}} := B_{i,5} \cdot \text{volt} \]
\[ T_{\text{alt}_i} := B_{i,6} \cdot \text{Nm} \]
\[ T_{\text{mot}_i} := B_{i,7} \cdot \text{Nm} \]
\[ P_i := B_{i,8} \cdot \text{kW} \]
\[ T_{W_i} := B_{i,10} \cdot \text{Nm} \]
\[ T_{\text{load}_i} := B_{i,11} \cdot \text{Nm} \]
\[ V_i := B_{i,12} \frac{\text{m}}{\text{sec}} \]
\[ U_{\text{capA}_i} := B_{i,9} \cdot \text{volt} \]
\[ \text{Speed}_6 := \text{Speed} \quad t_6 := t \quad N_6 := L \]

MOTOR START-UP
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

- Motor
- Load
- Alternator
- Wind Rotor

MOTOR START-UP
Data are stored in c:\matlab\ice\modeIdata\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 := READPRN(loadsc02)
Number of rows: L := rows(B) L = 1.654·10^3
Maximum time: T_max := B_{L-1,0} \cdot \text{sec} \quad T_{max} = 4 \cdot \text{sec}

i := 0 .. L - 1

\begin{align*}
\text{Time } t_i & := B_{i,0} \cdot \text{sec} \\
\text{Frequency } f_i & := B_{i,1} \cdot \text{Hz} \\
\text{Speed } \text{Speed}_i & := B_{i,2} \\
\text{Amp} & := B_{i,3} \text{amp} \\
\text{Motor Voltage } U_{mot_i} & := B_{i,4} \text{ volt} \\
\text{Alternator Voltage } U_{alt_i} & := B_{i,5} \text{ volt} \\
\text{Alternator Torque } T_{alt_i} & := B_{i,6} \text{ Nm} \\
\text{Motor Torque } T_{mot_i} & := B_{i,7} \text{ Nm} \\
\text{Motor Power } P_i & := B_{i,8} \text{ kW} \\
\text{Wind Torque } T_{w_i} & := B_{i,10} \text{ Nm} \\
\text{Load Torque } T_{load_i} & := B_{i,11} \text{ Nm} \\
\text{Voltage } V_i & := B_{i,12} \cdot \frac{m}{\text{sec}} \\
\text{Capacitor Voltage } U_{capA_i} & := B_{i,9} \text{ volt} \\
\end{align*}

\begin{align*}
\text{Speed } \text{Speed}_7 & := \text{Speed} \\
\text{Time } t_7 & := t \\
N_7 & := L
\end{align*}

\begin{align*}
\text{Wind Speed} \\
\text{Current}
\end{align*}

\begin{align*}
\text{Motor Start-Up}
\end{align*}
MOTOR PHASE VOLTAGE

ALTERNATOR PHASE VOLTAGE

VOLTAGE ACROSS CAPACITOR

ALTERNATOR OUTPUT POWER

FREQUENCY

MOTOR RPM

MOTOR ELECTROMAGNETIC TORQUE

ALTERNATOR TORQUE

- Motor
- Load
- Alternator
- Wind Rotor

MOTOR START-UP
APPENDIX K: Cost of Ice Analysis
Fuel Cost = $1.00/gallon

Note: Wind-Only and Wind-Diesel cases include icemaker modification cost of $5,000.
Fuel Cost = $1.25/gallon

Note: Wind-Only and Wind-Diesel cases include ice maker modification cost of $5,000.
**Fuel Cost = $1.50/gallon**

**Note:** Wind-Only and Wind-Diesel cases include icemaker modification cost of $5,000.
Fuel Cost = $1.75/gallon

Note: Wind-Only and Wind-Diesel cases include icemaker modification cost of $5,000.
Fuel Cost = $2.00/gallon

Note: Wind-Only and Wind-Diesel cases include icemaker modification cost of $5,000.
| No. | Description                  | Wind Prod | Wind Hrs | Diesel Hrs | Inkjet Hrs | Life Cycle | Battery Hrs | Gas Hrs | Inverter Gas Hrs | Load Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas Hrs | Loan Gas 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Hrs | Loan Gas Hr
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.