Starting Large AC Motors

For

IEEE Houston Section – CED Seminar

By:

Roy Cosse, P.E.
Robert Spiewak, P.E.

Presentation Code: 214

March 22-23, 2016

Synopsis:

Review induction and synchronous motor operation and effect on starting method selection. Equivalent circuit for start and operation. Reviews starting techniques for AC motors: direct-on-line, captive transformer, autotransformer, capacitor start, wye-delta, solid-state soft start, Adjustable Drive System (ASD), “pony driver” starting, and adjustable V/f isolated bus starting. Starting method selection (limited power and other restrictions).

Agenda

- Preliminaries
- Motor Fundamental
- Induction Motor

  Construction, basics, characteristics, and modeling
- Synchronous Motor

  Construction, basics, characteristics, and modeling
- Mechanical and Train Related Items

  Load characteristics, Inertia, Torque Consideration, Train Acceleration Time, Process Consideration, Protection Consideration
- Starting Techniques

  Induction and Synchronous Motor, Synchronous Motor Only, Special
- Calculations and Data Considerations

Preliminaries

Preliminaries

During seminar, we will provide background and examples to answer following two questions:

How to start motor?

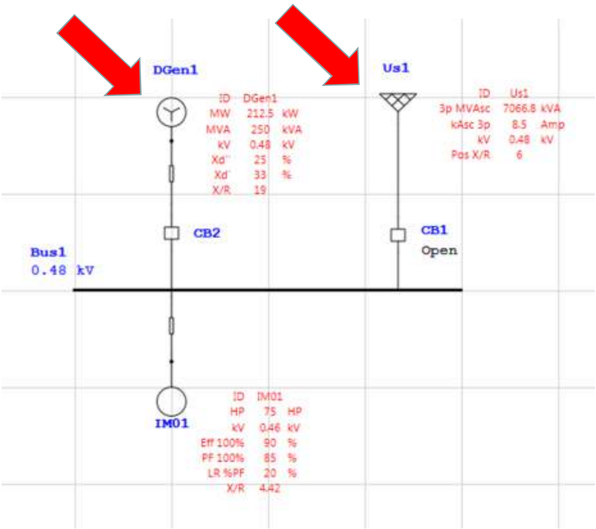
When motor is considered ***large*** for starting?

How to get data?

Something to think about…

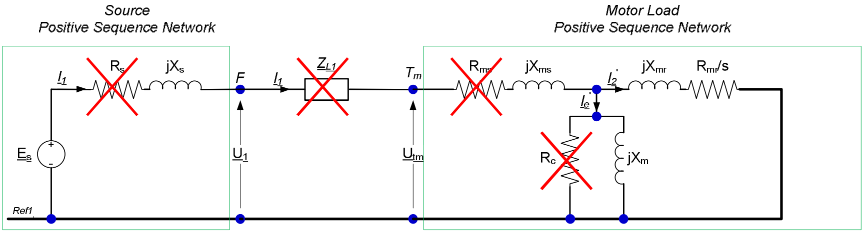
Preliminaries

Typical motor starting circuit for IM.



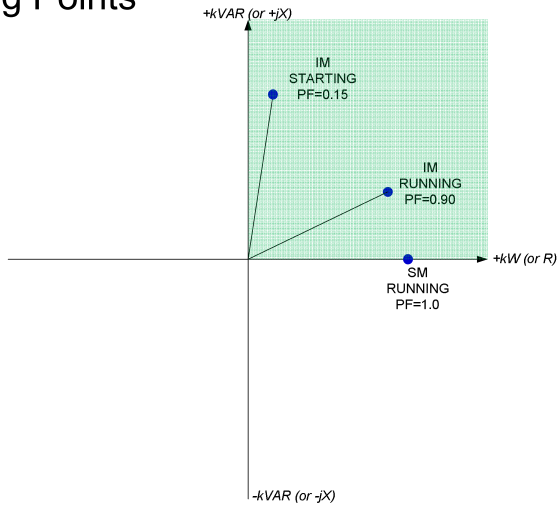
Preliminaries

- Equivalent circuit for IM connected to Utility



Preliminaries

- Operating Points



Preliminaries

Condition 1:

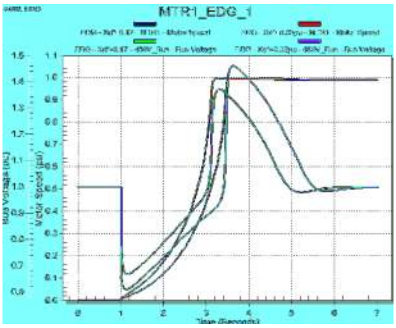
Typical diesel engine with "standard" synchronous generator (SG) X'', X'

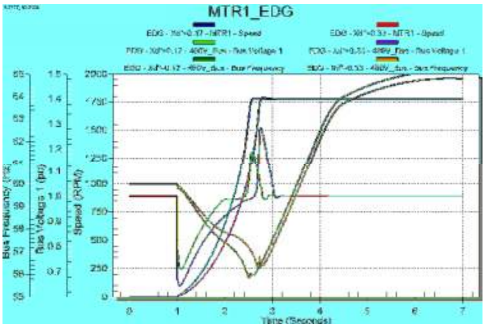
Condition 2:

SG is Low Voltage Transient (LVT) type with "adjusted" X'

Preliminaries

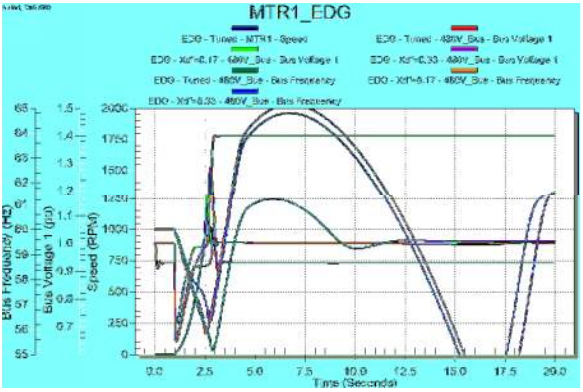
- Calculations





Preliminaries

- Calculations



Motor Fundamentals

Motor Fundamentals

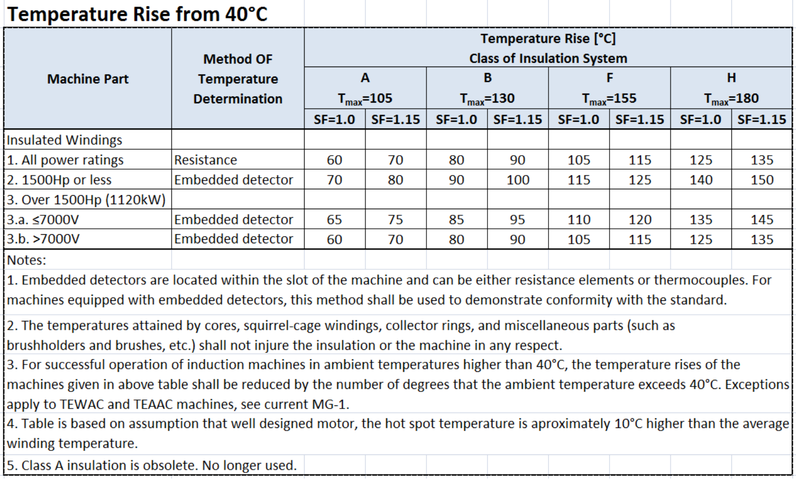
- Large motor definition
- Stator and Rotor Construction
- Insulation and Temperature Rise
- Mechanical/Torque Consideration
- Driver Selection IM/SM

Motor Fundamentals

- Small Machine (Fractional) – in general for O&G, continues rating ≤ 1 Hp
- Medium Machine (Integral) - in general for O&G, < 500Hp (n_s=3600,1800,1200rpm) etc.
- Large Machine – Larger than Medium Machine size/synchronous speed

Motor Fundamentals

- Insulation and Temperature Rise



Temperature Rise from 40°C

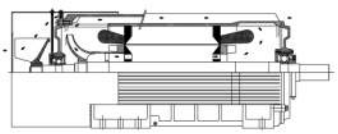
Machine Part	Method OF Temperature Determination	Temperature Rise [°C] Class of Insulation System							
		A T_{max}=105		B T_{max}=130		F T_{max}=155		H T_{max}=180	
		SF=1.0	SF=1.15	SF=1.0	SF=1.15	SF=1.0	SF=1.15	SF=1.0	SF=1.15
Insulated Windings									
1. All power ratings	Resistance	60	70	80	90	105	115	125	135
2. 1500Hp or less	Embedded detector	70	80	90	100	115	125	140	150
3. Over 1500Hp (1120kW)									
3.a. ≤7000V	Embedded detector	65	75	85	95	110	120	135	145
3.b. >7000V	Embedded detector	60	70	80	90	105	115	125	135

Notes:

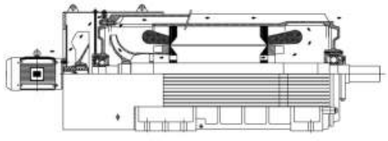
1. Embedded detectors are located within the slot of the machine and can be either resistance elements or thermocouples. For machines equipped with embedded detectors, this method shall be used to demonstrate conformity with the standard.
2. The temperatures attained by cores, squirrel-cage windings, collector rings, and miscellaneous parts (such as brushholders and brushes, etc.) shall not injure the insulation or the machine in any respect.
3. For successful operation of induction machines in ambient temperatures higher than 40°C, the temperature rises of the machines given in above table shall be reduced by the number of degrees that the ambient temperature exceeds 40°C. Exceptions apply to TEWAC and TEAAC machines, see current MG-1.
4. Table is based on assumption that well designed motor, the hot spot temperature is aproximately 10°C higher than the average winding temperature.
5. Class A insulation is obsolete. No longer used.

Motor Fundamentals

- Induction Motor - Cooling



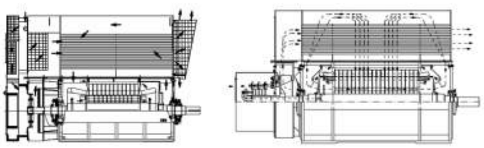
- Totally Enclosed
- Self-cooled
- IC411 (TEFC)
- IP55(W) / IP56(W) / IP65(W)



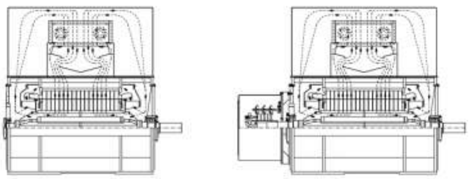
- Totally enclosed
- Forced cooling
- IC416 (TEBV)
- IP55(W) / IP56(W) / IP65(W)

Motor Fundamentals

- Induction Motor - Cooling



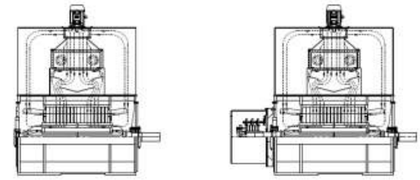
- Totally enclosed
- Air-to-air heat exchanger
- IC611 (TEAAC)
- IP55(W) / IP56(W) / IP65(W)
- MGF, MAF



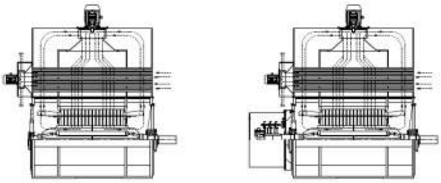
- Totally enclosed
- Air-to-water heat exchanger
- IC81W (TEWAC)
- IP55(W) / IP56(W) / IP65(W)
- MGW, MAW

Motor Fundamentals

- Induction Motor - Cooling



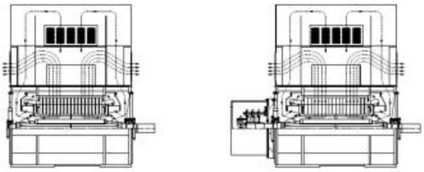
- Totally enclosed
- Independent cooling
- Air-to-water heat exchanger
- IC86W (TEWAC)
- IP55(W) / IP56(W) / IP65(W)
- MGL, MAL



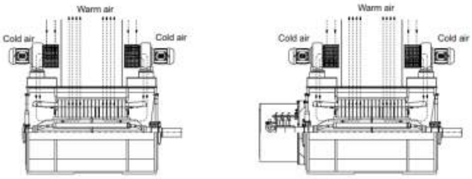
- Totally enclosed
- Independent cooling
- Air-to-air heat exchanger
- IC666 (TEAAC)
- IP55(W) / IP56(W) / IP65(W)
- MGI, MAI

Motor Fundamentals

- Induction Motor - Cooling



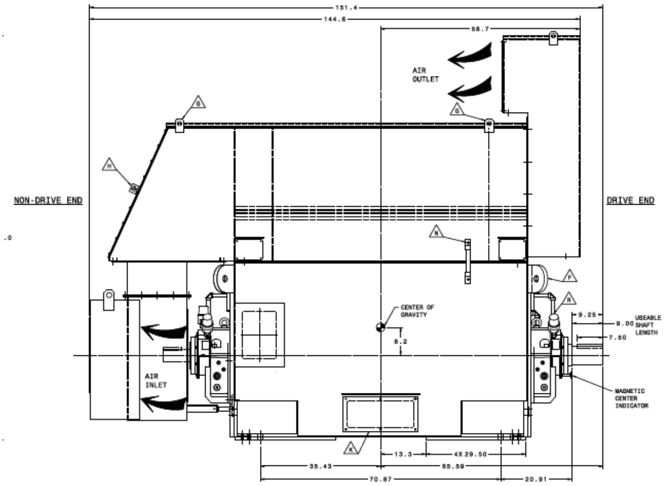
- Open (Self-cooled)
- IC01 (ODP)
- IP23 (WP-I)
- IP24(W) (WP-II)
- MGA, MAA, MGP, MAP



- Open
- Independent cooling
- IC06 (OIV)
- IP23 without ducts
- IC26 (OIV)
- IP24(W) with ducts
- MGV, MAV

Motor Fundamentals

- Induction Motor - Cooling



Motor Fundamentals

- **Code letters – Motor Inrush Characteristics**

Letter Designation	kVA per Horsepower*	Letter Designation	kVA per Horsepower*
A	0-3.15	K	8.0-9.0
B	3.15-3.55	L	9.0-10.0
C	3.55-4.0	M	10.0-11.2
D	4.0-4.5	N	11.2-12.5
E	4.5-5.0	P	12.5-14.0
F	5.0-5.6	R	14.0-16.0
G	5.6-6.3	S	16.0-18.0
H	6.3-7.1	T	18.0-20.0
J	7.1-8.0	U	20.0-22.4
		V	22.4-and up

*Locked kVA per horsepower range includes the lower figure up to, but not including, the higher figure. For example, 3.14 is designated by letter A and 3.15 by letter B.

Motor Fundamentals

- **Code letters**

  In general it is accepted that small motors requires higher starting kVA than larger motors. Standard 3PH motors often have these locked rotor codes:

  - <1 Hp: Locked Rotor Code L, 9.0-9.99 kVA
  - 1 - 2 Hp: Locked Rotor Code L or M, 9.0-11.19
  - 3 Hp : Locked Rotor Code K, 8.0-8.99
  - 5 Hp : Locked Rotor Code J, 7.1-7.99
  - 7.5 - 10 Hp : Locked Rotor Code H, 6.3-7.09
  - >15 Hp : Locked Rotor Code G, 5.6-6.29

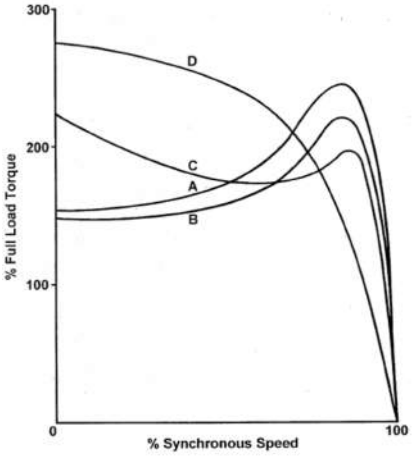
Motor Fundamentals

- **Design Type**

  Different motors of the same nominal horsepower can have varying starting current, torque curves, speeds, and other variables. Selection of a particular motor for an intended task must take all engineering parameters into account.

  The four NEMA designs have unique speed-torque-slip relationships making them suitable to different type of applications:

  - **NEMA design A**
  - **NEMA design B**
  - **NEMA design C**
  - **NEMA design D**



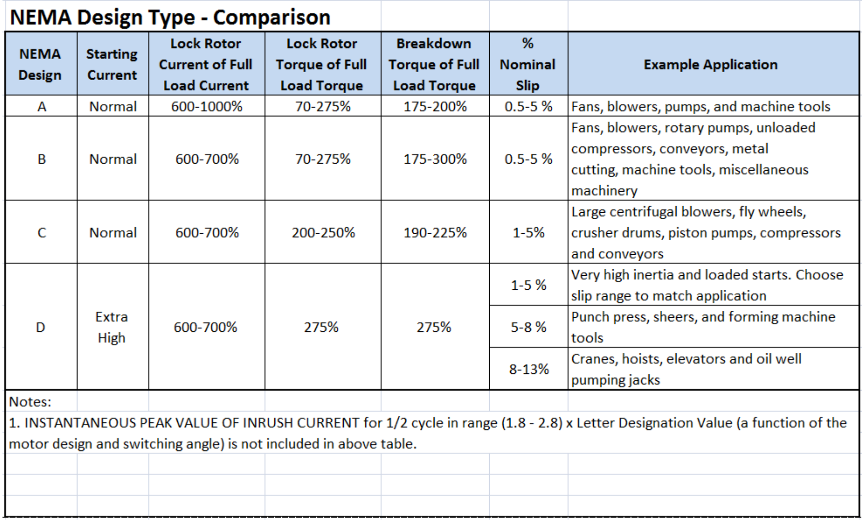
Motor Fundamentals

- **Design Type**
  - **NEMA design A**
    - maximum 5% slip
    - high to medium starting current
    - normal starting torque (150-170% of rated)
    - normal locked rotor torque
    - high breakdown torque
    - suited for a broad variety of applications - as **fans and pumps**
  - **NEMA design B**
    - maximum 5% slip
    - low starting current
    - high locked rotor torque
    - normal breakdown torque
    - suited for a broad variety of applications, normal starting torque - common in **HVAC application with fans, blowers and pumps**

Motor Fundamentals

- **Design Type**
  - **NEMA design C**
    - maximum 5% slip
    - low starting current
    - high locked rotor torque
    - normal breakdown torque
    - can’t sustain overload as design A or B
    - suited for equipment with high inertia starts - as **positive displacement pumps**
  - **NEMA design D**
    - maximum 5-13% slip
    - low starting current
    - very high locked rotor torque
    - Usually special order
    - suited for equipment with very high inertia starts - as **cranes, hoists** etc.

Motor Fundamentals



NEMA Design Type - Comparison

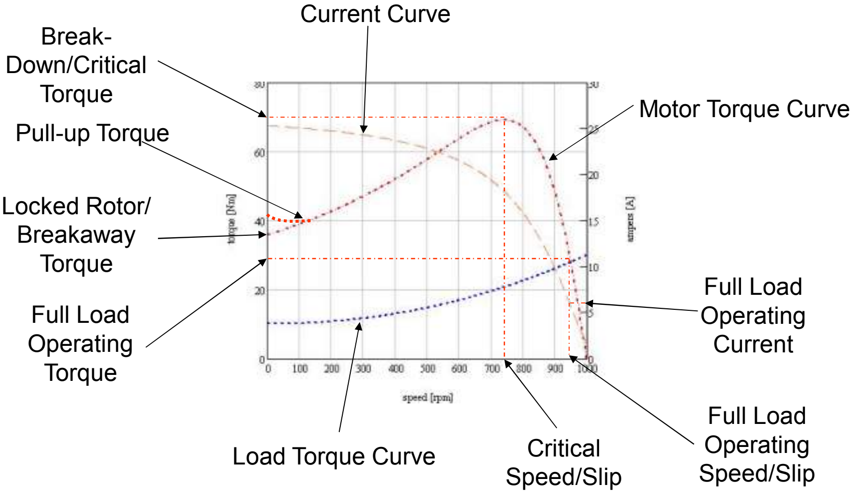
NEMA Design	Starting Current	Lock Rotor Current of Full Load Current	Lock Rotor Torque of Full Load Torque	Breakdown Torque of Full Load Torque	% Nominal Slip	Example Application
A	Normal	600-1000%	70-275%	175-200%	0.5-5 %	Fans, blowers, pumps, and machine tools
B	Normal	600-700%	70-275%	175-300%	0.5-5 %	Fans, blowers, rotary pumps, unloaded compressors, conveyors, metal cutting, machine tools, miscellaneous machinery
C	Normal	600-700%	200-250%	190-225%	1-5%	Large centrifugal blowers, fly wheels, crusher drums, piston pumps, compressors and conveyors
D	Extra High	600-700%	275%	275%	1-5 %	Very high inertia and loaded starts. Choose slip range to match application
					5-8 %	Punch press, sheers, and forming machine tools
					8-13%	Cranes, hoists, elevators and oil well pumping jacks

Notes:

1. INSTANTANEOUS PEAK VALUE OF INRUSH CURRENT for 1/2 cycle in range (1.8 - 2.8) x Letter Designation Value (a function of the motor design and switching angle) is not included in above table.

Motor Fundamentals

Type of Torques



Current Curve

Break-Down/Critical Torque

Pull-up Torque

Locked Rotor/ Breakaway Torque

Full Load Operating Torque

Motor Torque Curve

Full Load Operating Current

Load Torque Curve

Critical Speed/Slip

Full Load Operating Speed/Slip

Motor Fundamentals

Type of Torques (Both IM and SM)

- **Locked Rotor or Starting or Breakaway Torque (Static Torque)**

  Lock Rotor or Starting Torque (LRT) is the minimum torque the electrical motor will develop at rest for all angular positions of the rotor, with rated voltage applied at rated frequency

- **Pull-up Torque**

  The pull-up torque of an alternating-current motor is the minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs. For motors which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed up to rated speed.

- **Break-down Torque**

  The breakdown torque of a motor is the maximum torque which it will develop with rated voltage applied at rated frequency, without an abrupt drop in speed.

- **Full-load Torque or Braking Torque**

  The full-load torque (FLT) of a motor is the torque necessary to produce its rated horsepower at full-load speed. In pounds at a foot radius, it is equal to the horsepower times 5252 divided by the full-load speed.

Motor Fundamentals

Type of Torques (Only SM)

- **Pull-Out Torque**

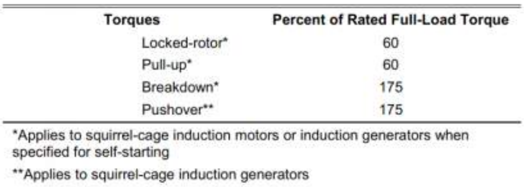
  The pull-out torque of a synchronous motor is the maximum sustained torque which the motor will develop at synchronous speed with rated voltage applied at rated frequency and with normal excitation

- **Pull-In Torque**

  The pull-up torque of an alternating-current motor is the minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs. For motors which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed up to rated speed.

Motor Fundamentals

The **standard torque** (implied; do not have to be specified), with rated voltage and frequency applied, shall be not less than the following:

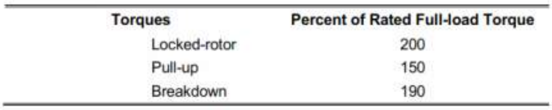


Torques	Percent of Rated Full-Load Torque
Locked-rotor*	60
Pull-up*	60
Breakdown*	175
Pushover**	175

*Applies to squirrel-cage induction motors or induction generators when specified for self-starting

**Applies to squirrel-cage induction generators

The **high torque** (when specified), with rated voltage and frequency applied, shall be not less than the following:



Torques	Percent of Rated Full-load Torque
Locked-rotor	200
Pull-up	150
Breakdown	190

Motor Fundamentals

The **custom load curve** (when specified), with rated voltage and frequency applied, may be lower than Normal and High Torque requirements, but the motor developed torque exceeds the load torque by a minimum of 10% of the rated full-load torque and any speed up to that at breakdown torque occurs.

Note: Since the torque developed by the induction machine at any speed is approximately proportional to the square of the voltage and inversely proportional to the square of the frequency it is desirable to determine what voltage and frequency variations will actually occur at each installation, taking into account any voltage drop resulting from the starting current drawn by the machine. This information and the torque requirements of the driven (or driving) machine define the machine speed-torque curve, at rated voltage and frequency, which is adequate for the application.

Note: A torque margin of lower than 10% is subject to individual agreements between manufacturer and user.

Motor Fundamentals

For **<u>“Low Inrush Motors”</u>** i.e. motors with 4.5 pu and lower lock-rotor current above values do not apply. Break down torque shall be not less than 150% of rated full-load torque, and break away torque and pull-up torque do not have any restrictions.

Motor Fundamentals

- Operation of IM from Variable –Frequency or Variable-Voltage power supplies, or both

  Induction machines to be operated from solid-state or other types of variable-frequency or variable-voltage power supplies, or both, for adjustable-speed applications may require individual consideration to provide satisfactory performance. Especially for operation below rated speed, it may be necessary to reduce the machine nameplate rating to avoid overheating. The ***induction machine manufacturer should be consulted before selecting a machine for such applications!***

Motor Fundamentals

- Starting Conditions (MG-1).

  IM with performance characteristics as described can accelerate load without damage or injurious temperature, for

  - **Standard Torque** with load inertia (WK^2) not exceeding

$$\text{Load } Wk^2 = A\left[\frac{Hp^{0.95}}{\left(\frac{RPM}{1000}\right)^{2.4}}\right] - 0.0685\left[\frac{Hp^{1.5}}{\left(\frac{RPM}{1000}\right)^{1.8}}\right]$$

Where:

A = 24 for 300 to 1800 rpm, inclusive, motors
A = 27 for 3600 rpm motors

  - **High Torque** with load inertia not exceeding 50% of above value.

Motor Fundamentals

- Number of Starts

Squirrel-cage induction motors specified to start and accelerate a connected load shall be capable of making the following starts, providing the WK^2 of the load, the load torque during acceleration, the applied voltage, and the method of starting are those for which the motor was designed.

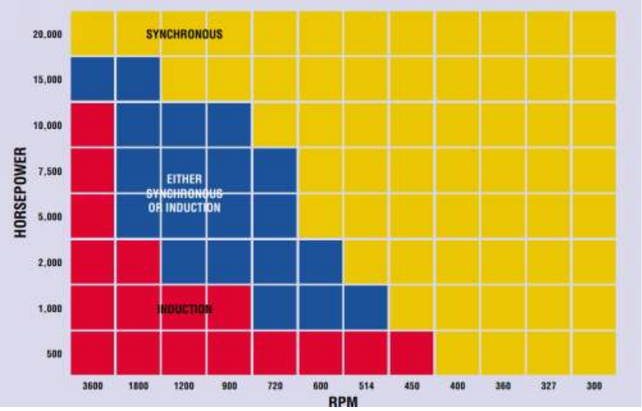
- Two starts in succession, coasting to rest between starts, with the motor initially at ambient temperature.
- One start with the motor initially at a temperature not exceeding its rated load operating temperature.

Note: If additional starts are required, it is recommended that none be made until all conditions affecting operation have been thoroughly investigated and the apparatus has been examined for evidence of excessive heating. It should be recognized that the number of starts should be kept to a minimum since the life of the motor is affected by the number of starts.

Motor Fundamentals

- Selecting Driver

  General areas of application of SM and IM

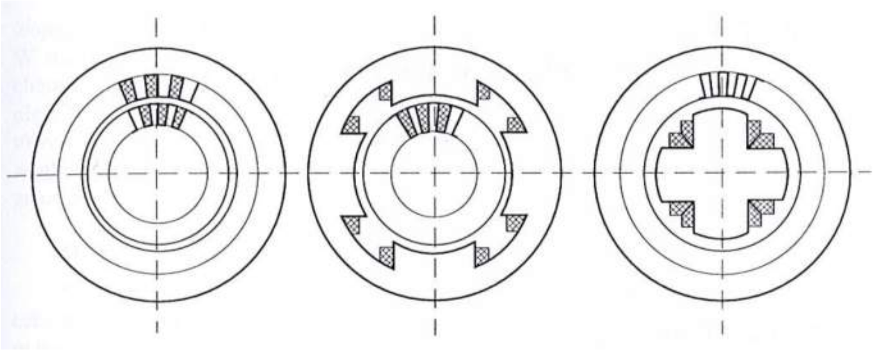


Motor Fundamentals

- Selecting Driver - Other factors:
  - VAR support for start and reacceleration
  - Current pulsation (reciprocating compressors)
  - Power supply size, type, connection etc.
  - Grid vs. Island
  - Stability (start, faults, other motor starts)
  - Harmonics
  - Sub-Synchronous Resonance (SSR) torque interactions

Motor Fundamentals

- Stator (ST) and Rotor (RT) configurations



ST: Cylindrical
RT: Cylindrical

ST: Silent Pole
RT: Cylindrical

ST: Cylindrical
RT: Silent Pole

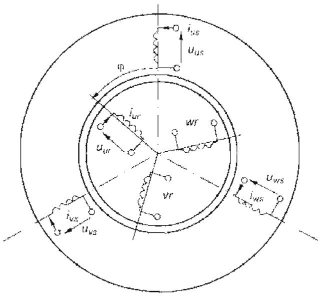
Induction Motor

Induction Motor

- Basics, type characteristics, load characteristics, and modeling
  - Motor modeling
  - General construction and Cooling
  - Induction motor - General data, principle of operation and nameplate information describing motor
  - Motor types and characteristics, application consideration
  - Equivalent motor parameters
  - Other consideration

Induction Motor

- General-Non-linear Model – Squirrel-cage rotor IM



$$\begin{cases} \boldsymbol{u}_{\boldsymbol{s}}^{abc} = \boldsymbol{r}_{\boldsymbol{s}}^{abc}\, \boldsymbol{i}_{\boldsymbol{s}}^{abc} + \dfrac{d}{dt}\boldsymbol{M}_{\boldsymbol{ss}}^{abc}\, \boldsymbol{i}_{\boldsymbol{s}}^{abc} + \dfrac{d}{dt}\boldsymbol{M}_{\boldsymbol{sr}}^{abc}\, \boldsymbol{i}_{\boldsymbol{r}}^{abc} \\ \boldsymbol{0} = \boldsymbol{r}_{\boldsymbol{r}}^{abc}\, \boldsymbol{i}_{\boldsymbol{r}}^{abc} + \dfrac{d}{dt}\boldsymbol{M}_{\boldsymbol{rr}}^{abc}\, \boldsymbol{i}_{\boldsymbol{r}}^{abc} + \dfrac{d}{dt}\boldsymbol{M}_{\boldsymbol{rs}}^{abc}\, \boldsymbol{i}_{\boldsymbol{s}}^{abc} \\ T_{em}(\boldsymbol{i}_{\boldsymbol{s}}^{abc}, \boldsymbol{i}_{\boldsymbol{r}}^{abc}, \omega) = \dfrac{1}{2}[\boldsymbol{i}_{\boldsymbol{s}}^{abc} \quad \boldsymbol{i}_{\boldsymbol{r}}^{abc}] \begin{bmatrix} \boldsymbol{0} & \dfrac{\partial}{\partial\omega}\boldsymbol{M}_{\boldsymbol{sr}}^{abc} \\ \dfrac{\partial}{\partial\omega}\boldsymbol{M}_{\boldsymbol{rs}}^{abc} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{i}_{\boldsymbol{s}}^{abc} \\ \boldsymbol{i}_{\boldsymbol{r}}^{abc} \end{bmatrix} \\ T_{mech}(\omega) = a_0 + a_1\omega + a_2\omega^2 + \cdots + a_n\omega^n \\ J\dfrac{d^2\omega}{dt^2} + k_d\dfrac{d\omega}{dt} = T_{em}(\boldsymbol{i}_{\boldsymbol{s}}^{abc}, \boldsymbol{i}_{\boldsymbol{r}}^{abc}, \omega) - T_{mech}(\omega) - T_{Loss} - B_r\omega \end{cases}$$

Induction Motor

- After Arbitrary Reference Frame Transform

$$\begin{cases}
u_{qs} = r_s i_{qs} + \frac{d}{dt}\lambda_{qs} + \omega\lambda_{ds} \\
u_{ds} = r_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega\lambda_{ds} \\
u_{0s} = r_s i_{0s} + \frac{d}{dt}\lambda_{0s} \\
u'_{qr} = r'_r i'_{qr} + \frac{d}{dt}\lambda'_{qr} + (\omega - \omega_r)\lambda'_{dr} \\
u'_{dr} = r'_r i'_{dr} + \frac{d}{dt}\lambda'_{dr} - (\omega - \omega_r)\lambda'_{qr} \\
u'_{0r} = r'_r i'_{0r} + \frac{d}{dt}\lambda'_{0r} \\
T_{em}\left(i_s^{qd0}, i_r^{qd0}\right) = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \\
\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \\ \lambda'_{qr} \\ \lambda'_{dr} \\ \lambda'_{0r} \end{bmatrix} = \begin{bmatrix} L_{ls} + L_m & 0 & 0 & L_m & 0 & 0 \\ 0 & L_{ls} + L_m & 0 & 0 & L_m & 0 \\ 0 & 0 & L_{ls} & 0 & 0 & 0 \\ L_m & 0 & 0 & L'_{lr} + L_m & 0 & 0 \\ 0 & L_m & 0 & 0 & L'_{lr} + L_m & 0 \\ 0 & 0 & 0 & 0 & 0 & L'_{lr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} \\
T_{mech}(\omega) = a_0 + a_1\omega + a_2\omega^2 + \cdots + a_n\omega^n \\
J\frac{d^2\omega}{dt^2} + k_d\frac{d\omega}{dt} = T_{em}(i_s^{qd0}, i_r^{qd0}) - T_{mech}(\omega) - T_{Loss} - B_r\omega
\end{cases}$$

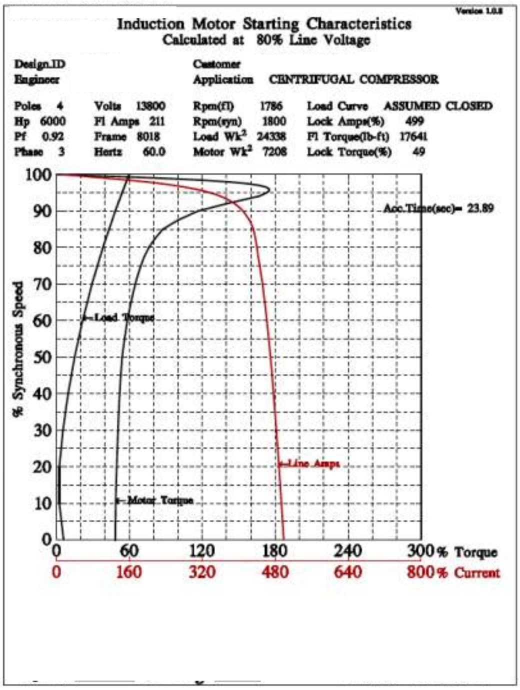
Induction Motor

- Steady State Us=const

$$\begin{cases}
V_{as} = (r_s + j\omega_e L_{ls})I_{as} + jL_m(I_{as} + I'_{ar}) \\
V'_{ar} = (r'_r + js\omega_e L'_{lr})I'_{ar} + js\omega_e L_m(I_{as} + I'_{ar}) \\
T_{em} = 3\frac{1}{\omega_{sm}} {I'_{ar}}^2 \frac{r'_r}{s} \\
T_{mech}(\omega) = a_0 + a_1\omega + a_2\omega^2 + \cdots + a_n\omega^n \\
J\frac{d^2\omega}{dt^2} + k_d\frac{d\omega}{dt} = T_{em}(i_s^{qd0}, i_r^{qd0}) - T_{mech}(\omega) - T_{Loss} - B_r\omega
\end{cases}$$

Induction Motor

- Typical Starting Curves



Version 1.0.8

Induction Motor Starting Characteristics
Calculated at 80% Line Voltage

Design.ID
Engineer
Customer
Application CENTRIFUGAL COMPRESSOR

Poles	4	Volts	13800	Rpm(fl)	1786	Load Curve	ASSUMED CLOSED
Hp	6000	Fl Amps	211	Rpm(syn)	1800	Lock Amps(%)	499
Pf	0.92	Frame	8018	Load Wk^2	24338	Fl Torque(lb-ft)	17641
Phase	3	Hertz	60.0	Motor Wk^2	7208	Lock Torque(%)	49

Acc.Time(sec)= 23.89

Induction Motor - Frames

Induction Motor - Stator

- High Speed

- Low Speed

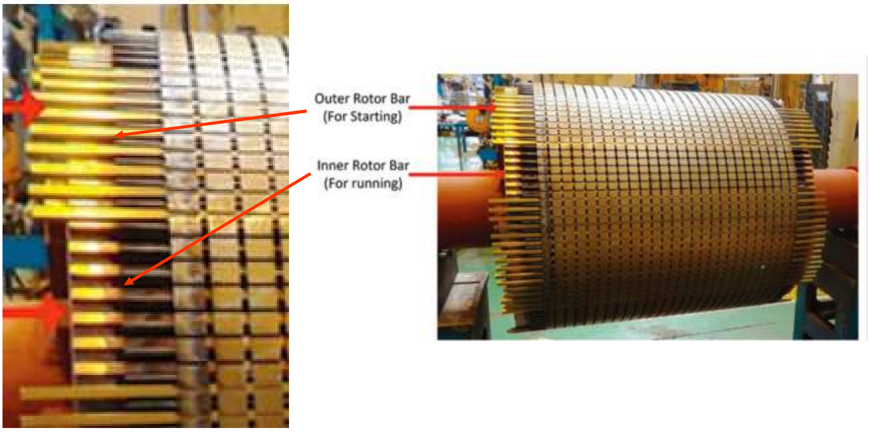
Induction Motor - Rotor

- High Speed
  4-6 Pole

- Medium Speed
  8-14 Pole

Induction Motor - Rotor

- Double-cage rotor bar construction for low inrush current motors



Induction Motor

General data

Motor electro-mechanical characteristics are described by:

- Nominal Voltage
- Nominal frequency
- Nominal Current
- Number of phases
- Number of poles
- Design class
- Code letter
- Moment of inertia
- All others (rated power factor, efficiency, excitation current etc.)

Induction Motor

General data

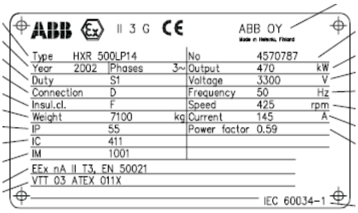


ABB II 3 G CE ABB OY

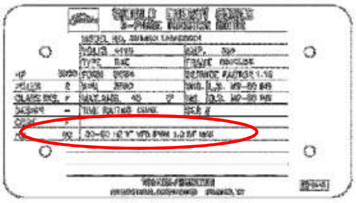
Made in Helsinki, Finland

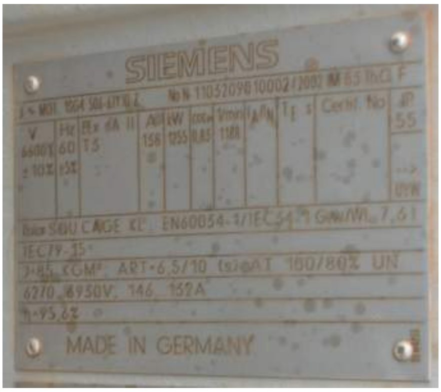
Type	HXR 500LP14			No	4570787	
Year	2002	Phases	3~	Output	470	kW
Duty	S1			Voltage	3300	V
Connection	D			Frequency	50	Hz
Insul.cl.	F			Speed	425	rpm
Weight	7100		kg	Current	145	A
IP	55			Power factor	0.59	
IC	411					
IM	1001					

EEx nA II T3, EN 50021

VTT 03 ATEX 011X

IEC 60034-1





SIEMENS

EN60034-1/IEC34-1

IEC79-15

MADE IN GERMANY

Induction Motor

General data

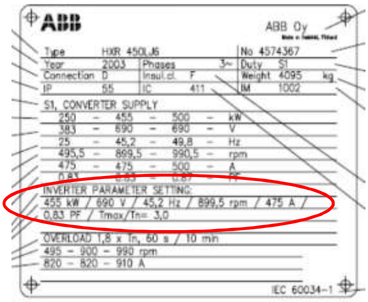


ABB ABB Oy

Type	HXR 450LJ6			No	4574367	
Year	2003	Phases	3~	Duty	S1	
Connection	D	Insul.cl.	F	Weight	4095	kg
IP	55	IC	411	IM	1002	

S1, CONVERTER SUPPLY

250 – 455 – 500 – kW

383 – 690 – 690 – V

25 – 45,2 – 49,8 – Hz

495,5 – 899,5 – 990,5 – rpm

475 – 475 – 500 – A

0,83 – 0,83 – 0,87 – PF

INVERTER PARAMETER SETTING:

455 kW / 690 V / 45,2 Hz / 899,5 rpm / 475 A /

0,83 PF / Tmax/Tn= 3,0

OVERLOAD 1,8 x Tn, 60 s / 10 min

495 – 900 – 990 rpm

820 – 820 – 910 A

IEC 60034-1

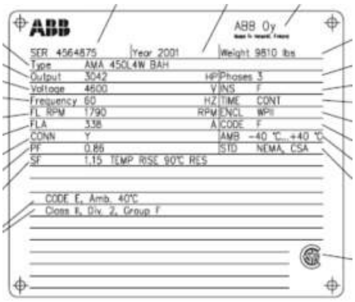


ABB ABB Oy

SER 4564875	Year 2001		Weight 9810 lbs	
Type	AMA 450L4W BAH			
Output	3042	HP	Phases	3
Voltage	4600	V	INS	F
Frequency	60	HZ	TIME	CONT
FL RPM	1790	RPM	ENCL	WPII
FLA	338	A	CODE	F
CONN	Y		AMB	-40 °C...+40 °C
PF	0.86		STD	NEMA, CSA
SF	1.15 TEMP RISE 90°C RES			

CODE F, Amb. 40°C

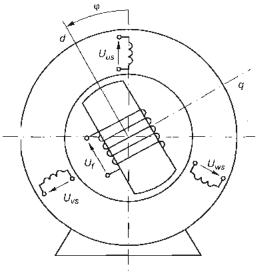
Class I, Div. 2, Group F

Synchronous Motor

Synchronous Motor

Synchronous Motor

- General-Non-linear Model



$$\begin{cases} \boldsymbol{u}_s^{abc} = \boldsymbol{r}_s^{abc}\boldsymbol{i}_s^{abc} + \frac{d}{dt}\boldsymbol{M}_{ss}^{abc}\,\boldsymbol{i}_s^{abc} + \frac{d}{dt}\boldsymbol{M}_{sf}^{abc}\boldsymbol{i}_f \\ \boldsymbol{u}_f = \boldsymbol{r}_f\boldsymbol{i}_f + \frac{d}{dt}\boldsymbol{M}_{ff}\boldsymbol{i}_f + \frac{d}{dt}\boldsymbol{M}_{fs}^{abc}\boldsymbol{i}_s^{abc} \\ T_{em}(\boldsymbol{i}_s^{abc}, \boldsymbol{i}_f, \omega) = \frac{1}{2}\left[\boldsymbol{i}_s^{abc} \quad \boldsymbol{i}_f\right] \begin{bmatrix} \boldsymbol{0} & \frac{\partial}{\partial\omega}\boldsymbol{M}_{sf}^{abc} \\ \frac{\partial}{\partial\omega}\boldsymbol{M}_{fs}^{abc} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{i}_s^{abc} \\ \boldsymbol{i}_f \end{bmatrix} \\ T_{mech}(\omega) = a_0 + a_1\omega + a_2\omega^2 + \cdots + a_n\omega^n \\ J\frac{d^2\omega}{dt^2} + k_d\frac{d\omega}{dt} = T_{em}(\boldsymbol{i}_s^{abc}, \boldsymbol{i}_f, \omega) - T_{mech}(\omega) - T_{Loss} - B_r\omega \end{cases}$$

Synchronous Motor

- Park’s Transform

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\varphi & \cos(\varphi - 120°) & \cos(\varphi - 240°) \\ -\sin\varphi & -\sin(\varphi - 120°) & -\sin(\varphi - 240°) \end{bmatrix}$$

$$u_d = R_s i_d + \frac{\mathrm{d}}{\mathrm{d}t}\psi_d - \dot{\varphi}\psi_q$$

$$u_q = R_s i_q + \frac{\mathrm{d}}{\mathrm{d}t}\psi_q + \dot{\varphi}\psi_d$$

$$u_f = R_f i_f + \frac{\mathrm{d}}{\mathrm{d}t}\psi_f$$

$$J\frac{d^2\varphi}{dt^2} + k_d d\frac{\varphi}{dt} = T_e + T_m$$

$$T_e = \psi_d i_q - \psi_q i_d$$

Synchronous Motor

- Steady State Us=const

$$i_{us}=\sqrt{\frac{2}{3}}(I_d\cos\varphi - I_q\sin\varphi) = \frac{U_{sm}\cos\vartheta - E_{fm}}{X_d}\cos(\omega_0 t + \varphi_0) + \frac{U_{sm}\sin\vartheta}{X_q}\sin(\omega_0 t + \varphi_0) =$$

$$= \frac{U_{sm}\cos\vartheta - E_{fm}}{X_d}\sin(\omega_0 t + \vartheta) - \frac{U_{sm}\sin\vartheta}{X_q}\cos(\omega_0 t + \vartheta)$$

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \sqrt{\frac{3}{2}}U_{sm}\begin{bmatrix} \sin\vartheta \\ \cos\vartheta \end{bmatrix}$$

$$I_d = \sqrt{\frac{3}{2}}\frac{U_{sm}\cos\vartheta - E_{fm}}{X_d}$$

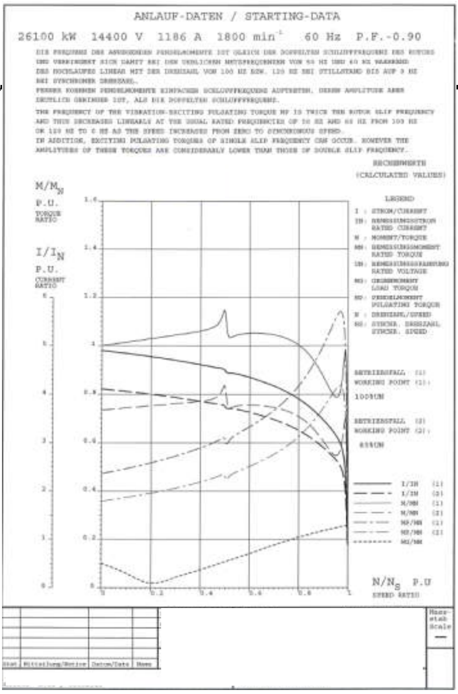
$$I_q = -\sqrt{\frac{3}{2}}\frac{U_{sm}}{X_q}\sin\vartheta$$

$$J\frac{d^2\varphi}{dt^2} + k_d d\frac{\varphi}{dt} = T_e + T_m$$

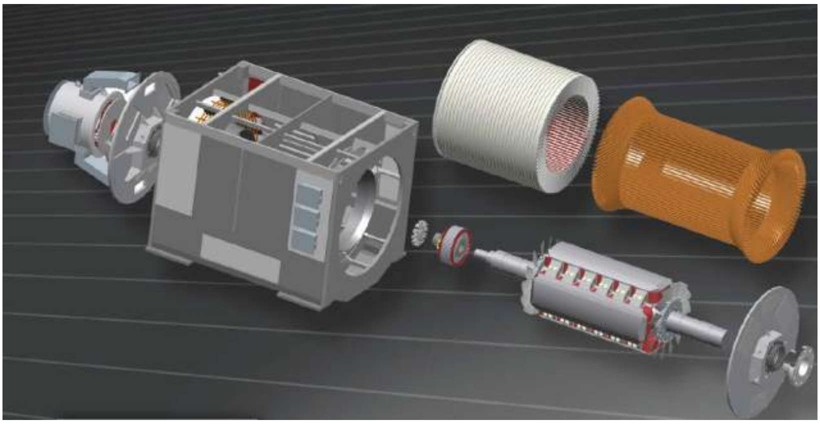
$$T_e = -\frac{1}{\omega_0}\left[\frac{3}{2}\frac{U_{sm}E_{fm}}{X_d}\sin\vartheta + \frac{3}{4}U_{sm}^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\vartheta\right]$$

Synchronous Motor

- Typical Starting Curves



Synchronous Motor



Stator

- High Speed
- Low Speed

Rotors

High Speed

4-6 Pole Solid Rotors

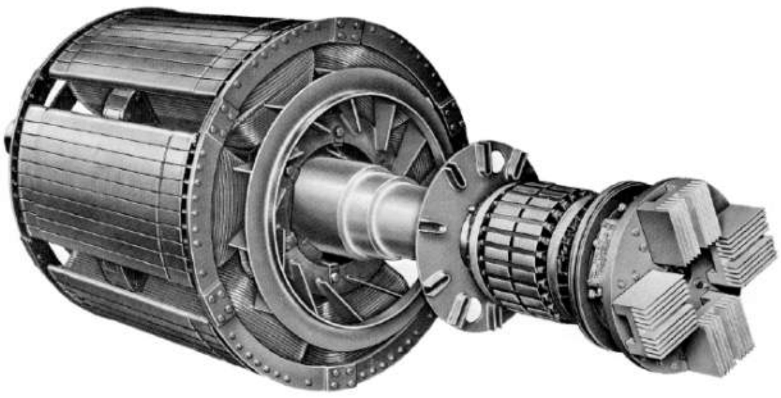
Medium Speed

8-14 Pole Stacked Rotors

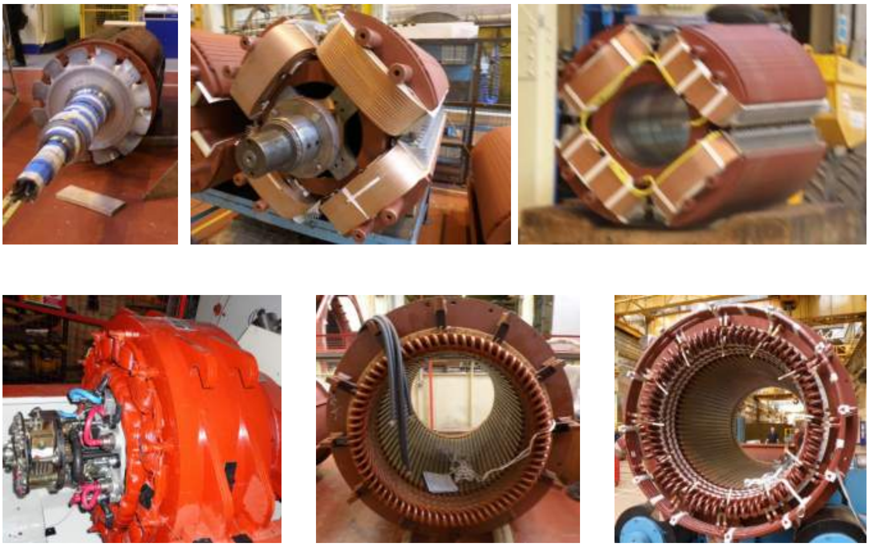
Low Speed

>14 Pole Stacked Rotors

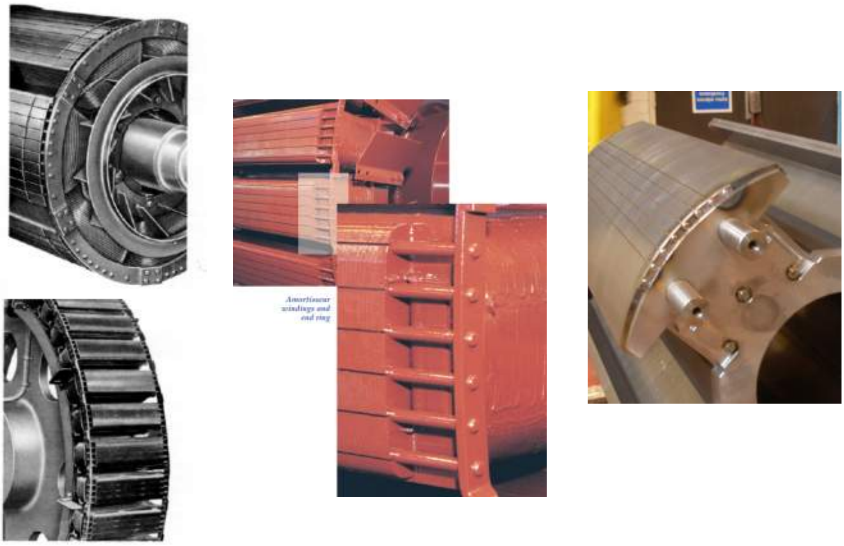
Synchronous Motor



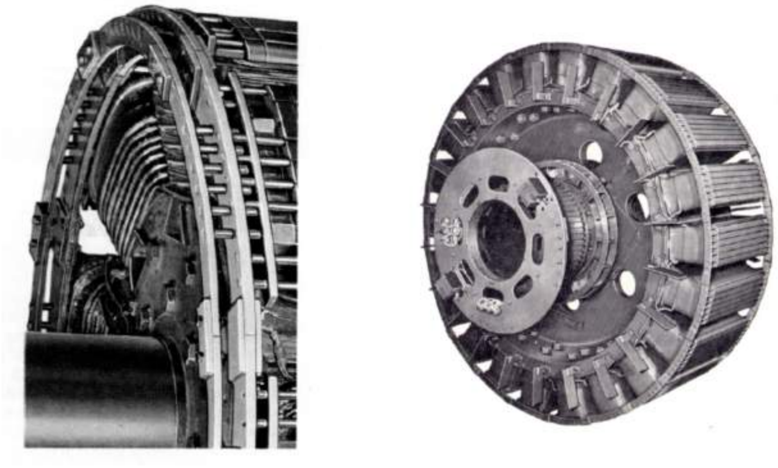
Synchronous Motor



Synchronous Motor



Synchronous Motor



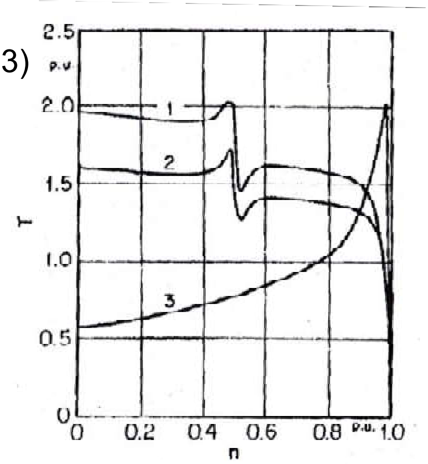
Synchronous Motor

General data

- Motor electro-mechanical characteristics are described by:
  - Nominal Voltage
  - Nominal frequency
  - Nominal Current
  - Number of phases
  - Number of poles
  - Design class
  - Code letter
  - Moment of inertia
  - All others (rated power factor, efficiency, excitation current etc.)

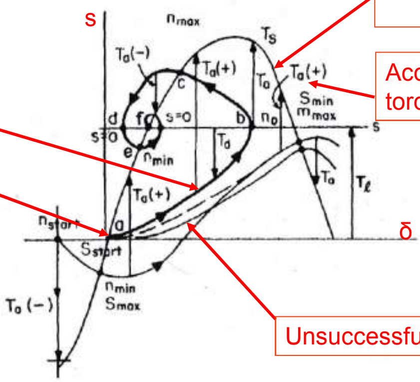
Synchronous Motor

- Characteristic torque curves:
  - 5kHp SM (1-PF=1.0)
  - 5kHp SM (2-PF=0.80)
  - 5kHp IM / squirrel-cage (3)



Synchronous Motor

- SM Synchronization – Torque trajectory



T_s (T_d, δ) = Motor torque

Acceleration torque T_a=T_s+T_d-T_l

Successful

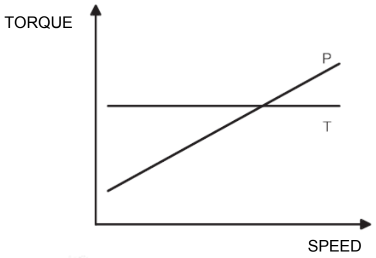
Closing angle =0

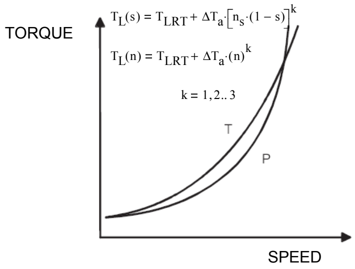
Unsuccessful

Mechanical Load
And
Train System

Load Types

- Constant Torque
- Variable Torque

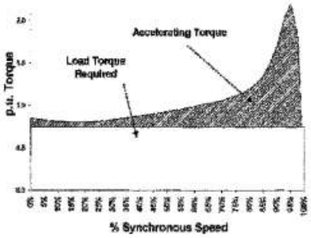


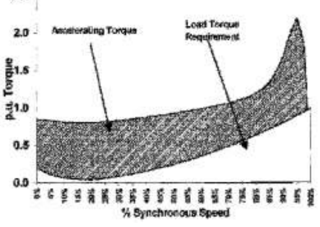


$$T_L(s) = T_{LRT} + \Delta T_a \cdot \left[n_s \cdot (1 - s)\right]^k$$

$$T_L(n) = T_{LRT} + \Delta T_a \cdot (n)^k$$

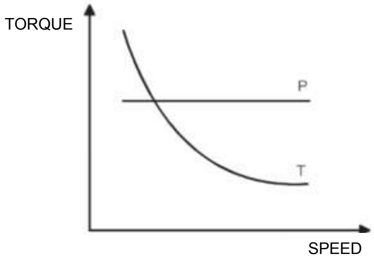
$$k = 1, 2..3$$

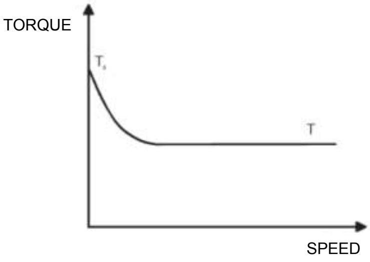




Load Types

- Constant Power
- Constant Torque w/ High Brake-Away

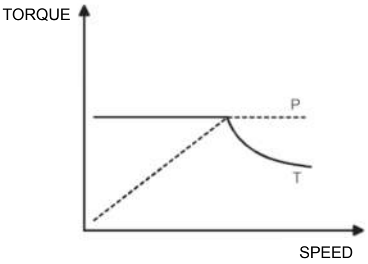


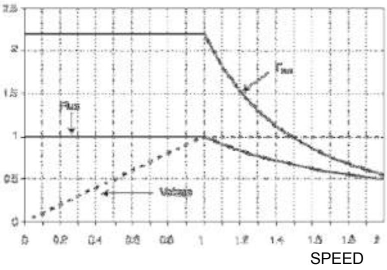


$$T_L(n) = A_o + B\cdot n + C\cdot n^2 + D\cdot n^3$$

Load Types

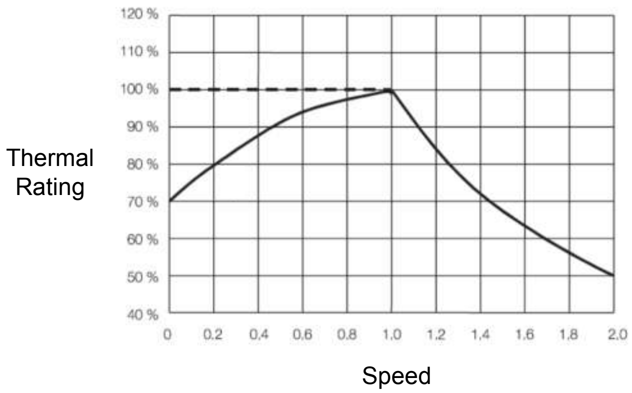
- Sub- and Super-Synchronous Applications





Load Types

- ASD Application of Standard Motors



Load Types

- Load Types

Application	Load Torque as a Minimum Percent Drive Torque		
	Breakaway	Accelerating	Peak Running
Blowers, centrifugal:			
Valve closed	30	50	40
Valve open	40	110	100
Blowers, positive displacement, rotary, bypass	40	40	100
Centrifuges	40	60	125
Compressors, axial-vane, loaded	40	100	100
Compressors, reciprocating, start unloaded	100	50	100
Conveyors, belt (loaded)	150	130	100
Conveyors, screw (loaded)	175	100	100
Conveyors, shaker-type (vibrating)	150	150	75
Fans, centrifugal, ambient:			
Valve closed	25	60	50
Valve open	25	110	100
Fans, centrifugal, hot:			
Valve closed	25	60	100
Valve open	25	200	175
Fans, propeller, axial-flow	40	110	100
Mixers, chemical	175	75	100
Mixers, slurry	150	125	100
Pumps, adjustable-blade, vertical	150	200	200
Pumps, centrifugal, discharge open	40	150	150
Pumps, oil-field, flywheel	40	150	150
Pumps, oil, lubricating	40	150	150
Pumps, oil, fuel	40	150	150
Pumps, propeller	40	100	100
Pumps, reciprocating, positive displacement	175	30	175
Pumps, screw-type, primed, discharge open	150	100	100
Pumps, slurry-handling, discharge open	150	100	100
Pumps, turbine, centrifugal, deep-well	50	100	100
Pumps, vacuum (paper mill service)	60	100	150
Pumps, vacuum (other applications)	40	60	100
Pumps, vane-type positive displacement	150	150	175

Inertia

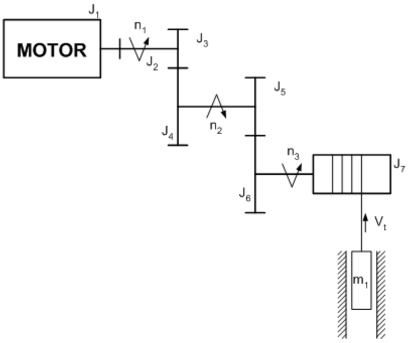
- Inertia

$$J_z = \sum_{i=1}^{w} J_i \cdot \left(\frac{n_i}{n_1}\right)^2 + \sum_{i=1}^{p} m_i \cdot \left(\frac{V_i}{n_1}\right)^2$$

w - numer rotating elements
p - number linera motion elements

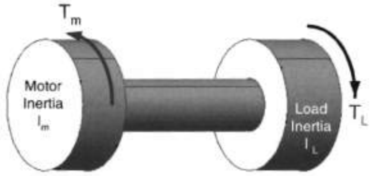
Inertia

- Inertia



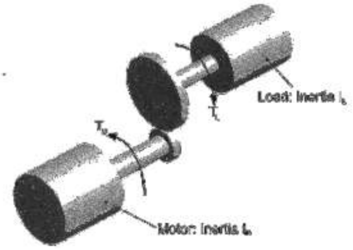
$$J_z = (J_1 + J_2 + J_3) \cdot \left(\frac{n_1}{n_1}\right)^2 + (J_4 + J_5) \cdot \left(\frac{n_2}{n_1}\right)^2 + (J_6 + J_7) \cdot \left(\frac{n_3}{n_1}\right)^2 + m_1 \cdot \left(\frac{V_1}{n_1}\right)^2$$

Torsion



$$T_m = T_L + \left(J_L + I_m\right)\cdot\left(\frac{d}{dt}n_m\right) + B\cdot n_m$$

Torsion



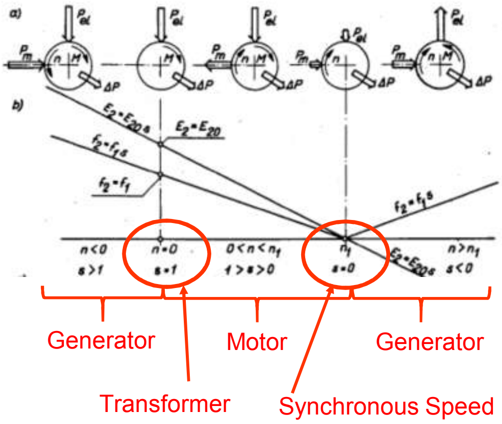
$$T_m = \frac{T_L}{N} + \left(J_L + I_m\cdot N^2\right)\cdot\left(\frac{d}{dt}n_m\right) + n_m\cdot\left(B_L + B_m\cdot N^2\right)$$

N - gear ratio
J - inertia
B - dumping

Induction Motor

Starting Methods

Motor Starting – Induction Machine



Generator

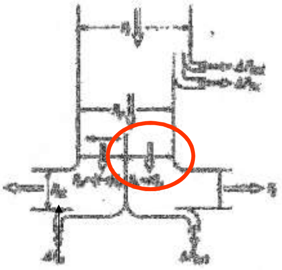
Motor

Generator

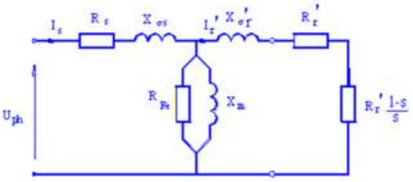
Transformer

Synchronous Speed

- Motoring Operation



- Equivalent circuit of one phase of induction motor



$$Z_s(f) := R_s + \frac{f}{f_n} \cdot j \cdot X_{\sigma s}$$

$$Z'_r(s,f) := \frac{R'_r}{s} + \frac{f}{f_n} \cdot j \cdot X'_{\sigma r}$$

$$Z_m := \frac{R_{fe} \cdot X_m \cdot j}{R_{fe} + X_m \cdot j}$$

$$Z_m(f) := \frac{\left(\frac{f}{f_n}\right)^{0.7} \cdot R_{fe} \cdot \frac{f}{f_n} \cdot X_m \cdot j}{\left(\frac{f}{f_n}\right)^{0.7} \cdot R_{fe} + \frac{f}{f_n} \cdot X_m \cdot j}$$

$$Z(s,f) := Z_s(f) + \frac{Z'_r(s,f) \cdot Z_m(f)}{Z'_r(s,f) + Z_m(f)}$$

$$U(f) := U_n \cdot \frac{f}{f_n}$$

$$n(s,f) := \frac{60 \cdot f}{p} \cdot (1 - s)$$

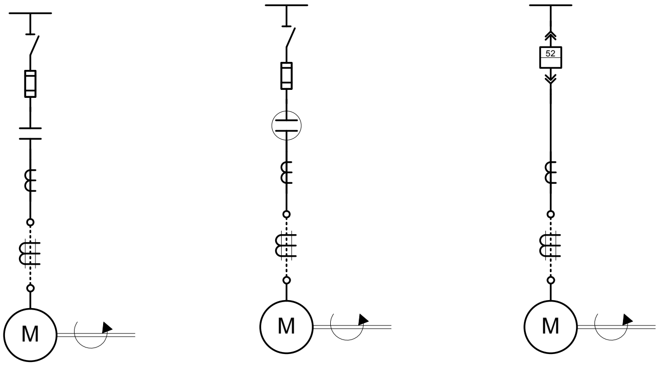
$$I_s(s,f) := \frac{U(f)}{\sqrt{3} \cdot Z(s,f)} \qquad I'_r(s,f) := I_s(s,f) \cdot \frac{Z_m(f)}{Z'_r(s,f) + Z_m(f)}$$

$$T_e(s,f) := \frac{3 \cdot p}{2 \cdot \pi \cdot f} \cdot \left(\left|I'_r(s,f)\right|\right)^2 \cdot \mathrm{Re}\left(Z'_r(s,f)\right)$$

Modification for Variable Frequency

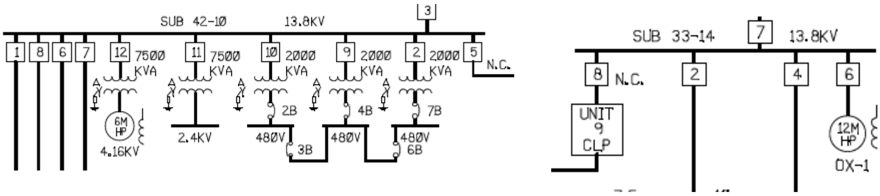
Motor Starting

- Direct On Line Starter (or DOL or FVNR)
  - One Line Representation



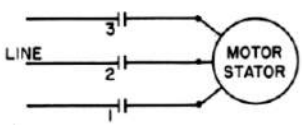
Motor Starting

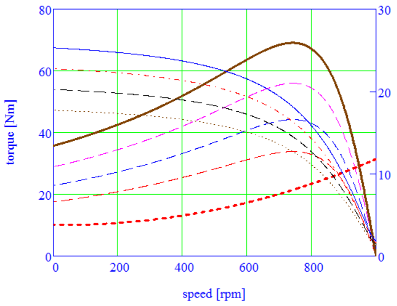
- Direct On Line Starter (or DOL or FVNR)
  - One Line Examples



Motor Starting

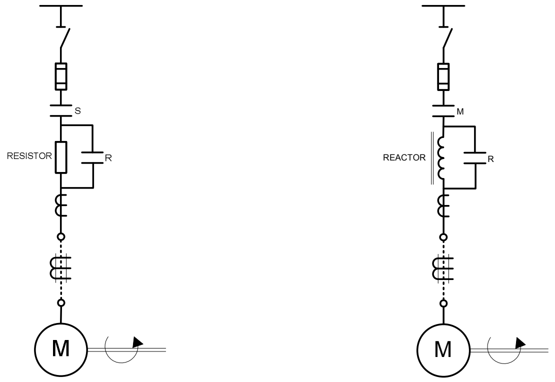
- Direct On Line Starter (or DOL or FVNR)
  - Characteristics





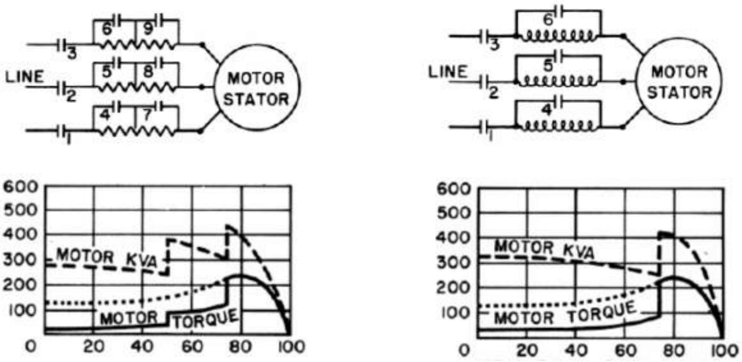
Motor Starting

- Reduce Voltage Resistor/Reactor Starter
  - One Line Representation



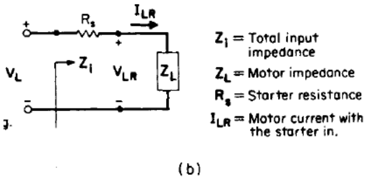
Motor Starting

- Reduce Voltage Resistor/Reactor Starter
  - Characteristics

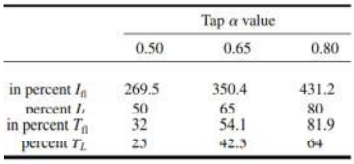


Motor Starting

- Reduce Voltage Resistor/Reactor Starter
  - Equivalent Diag.

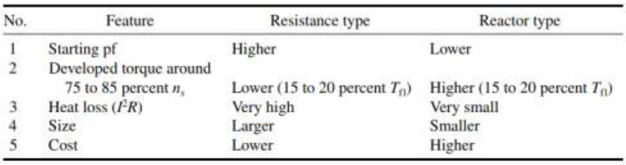


Motor Locked-Rotor Resistance Quantities with the Starter In



	Tap α value		
	0.50	0.65	0.80
in percent I_{fl}	269.5	350.4	431.2
percent I_L	50	65	80
in percent T_{fl}	32	54.1	81.9
percent T_L	23	42.3	64

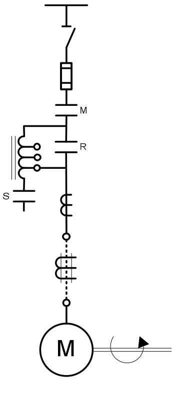
TABLE 5.3 Comparison of Resistance and Reactance Starting



No.	Feature	Resistance type	Reactor type
1	Starting pf	Higher	Lower
2	Developed torque around 75 to 85 percent n_s	Lower (15 to 20 percent T_{fl})	Higher (15 to 20 percent T_{fl})
3	Heat loss (I^2R)	Very high	Very small
4	Size	Larger	Smaller
5	Cost	Lower	Higher

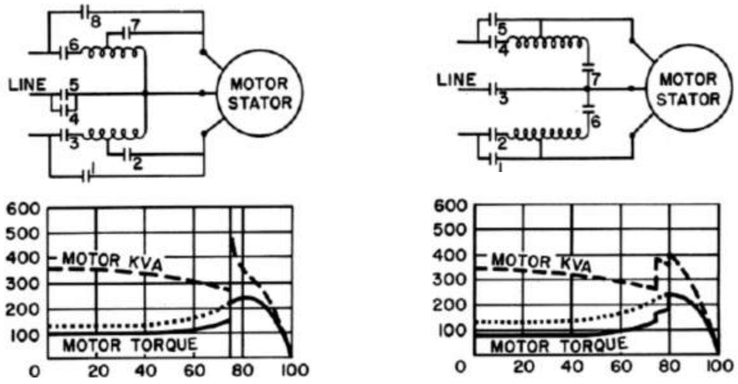
Motor Starting

- Reduce Voltage Autotransformer Starter (RVAT or Korndörfer Starter)
  - One Line Representation



Motor Starting

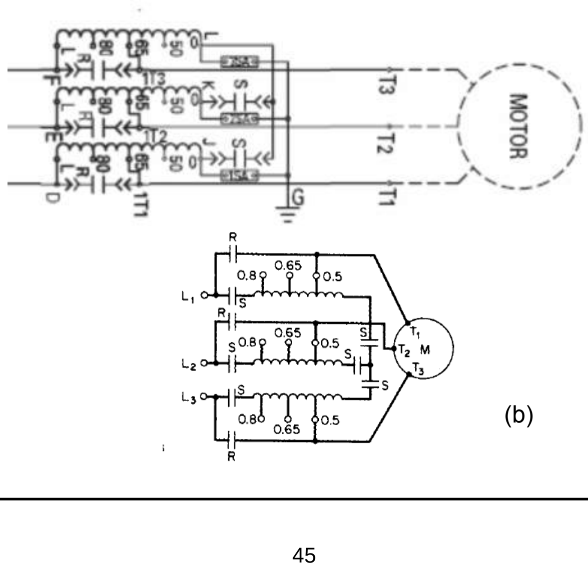
- Reduce Voltage Autotransformer Starter (RVAT or Korndörfer Starter) – 2-Winding XFMR
  - Characteristics



(a)

Motor Starting

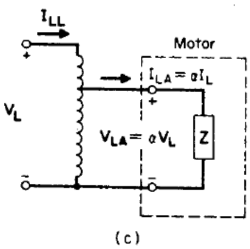
- Reduce Voltage Autotransformer Starter (RVAT or Korndörfer Starter) – 3-Winding XFMR



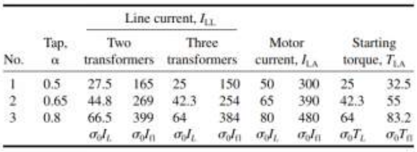
(b)

Motor Starting

- Reduce Voltage Autotransformer Starter (RVAT or Korndörfer Starter)
  - Equivalent Diag.



(c)

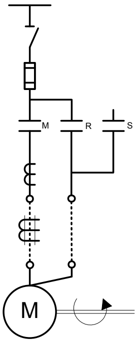


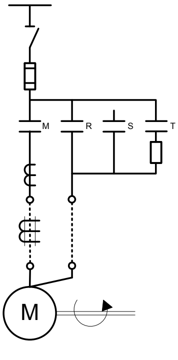
No.	Tap, α	Line current, I_{LL}				Motor current, I_{LA}		Starting torque, T_{LA}	
		Two transformers		Three transformers					
1	0.5	27.5	165	25	150	50	300	25	32.5
2	0.65	44.8	269	42.3	254	65	390	42.3	55
3	0.8	66.5	399	64	384	80	480	64	83.2
		$\sigma_0 I_L$	$\sigma_0 I_{fl}$	$\sigma_0 I_L$	$\sigma_0 I_{fl}$	$\sigma_0 I_L$	$\sigma_0 I_{fl}$	$\sigma_0 T_L$	$\sigma_0 T_{fl}$

α = voltage tap = V_{LA}/V_g
$I_{LA} = \alpha I_L$ = motor current
$I_{LL} = \alpha I_{LA} = \alpha^2 I_L$ = line current for (*b*)
$= \alpha^2 I_1 + 0.15\, I_{fl}$ for (*a*)
$T_A = \alpha^2 T$ = motor torque with autotransformer

Motor Starting

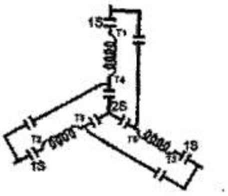
- Y / Δ (or Delta / WYE) Starter
  - One Line Representation

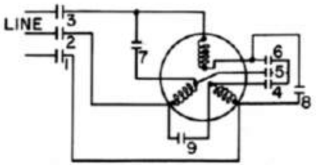


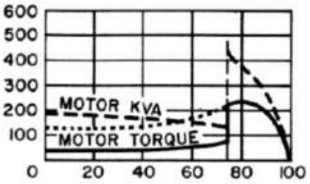


Motor Starting

- Y / ∆ (or Delta / WYE) Starter
  - Characteristics

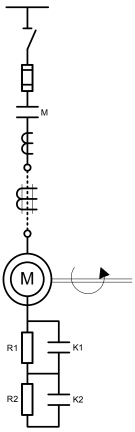






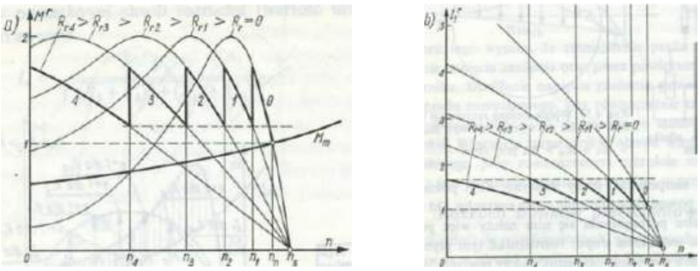
Motor Starting

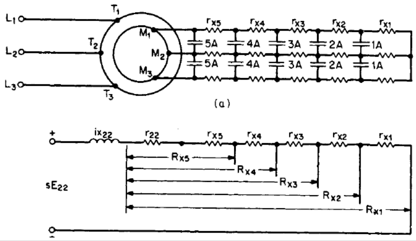
- Wound-rotor Resistance Starter (Slip-Ring Starter)
  - One Line Representation



Motor Starting

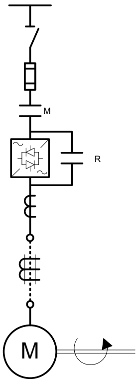
- Wound-rotor Resistance Starter (Slip-Ring Starter)
  - Principle





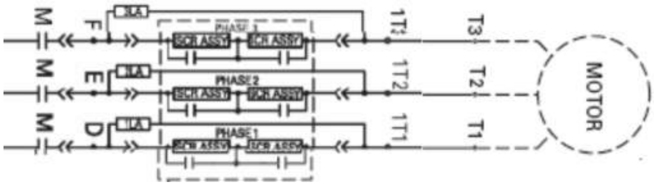
Motor Starting

- Reduce Voltage Solid State Starter with V=var, f=const (or RVSS)



Motor Starting

- Reduce Voltage Solid State Starter with V=var, f=const (or RVSS)

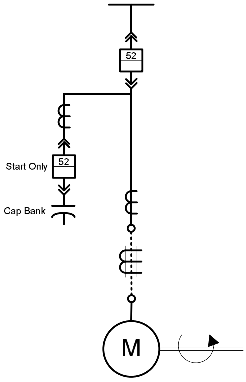


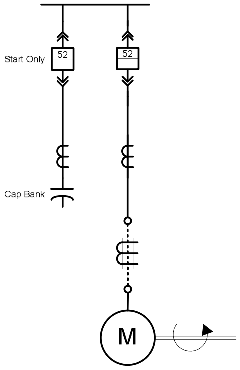
Motor Starting

- Reduce Voltage Solid State Starter with V=var, f=const (or RVSS)
  - Caution...

Motor Starting

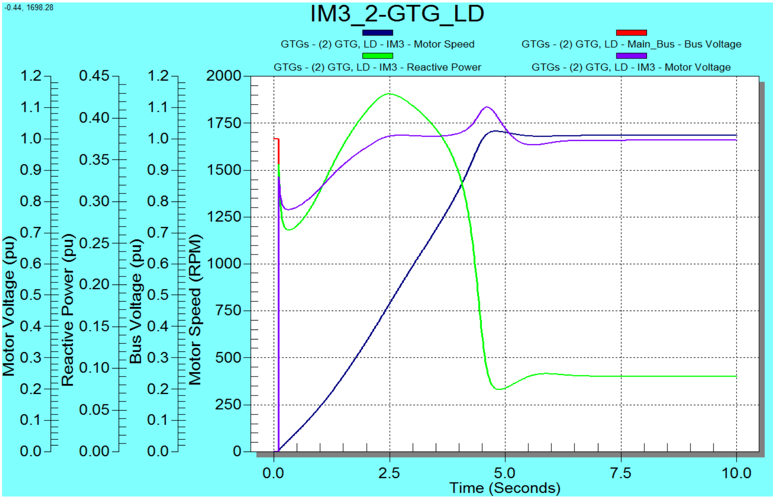
- Shunt Capacitor Starting
  - One Line Representation





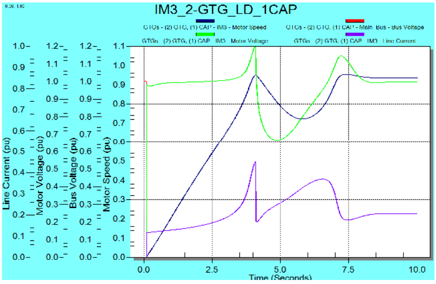
Motor Starting

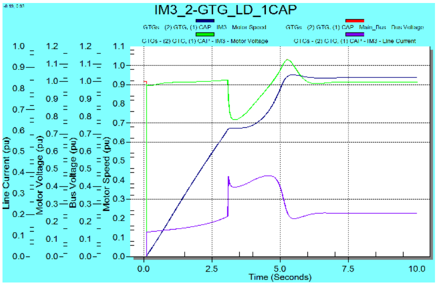
- Principle



Motor Starting

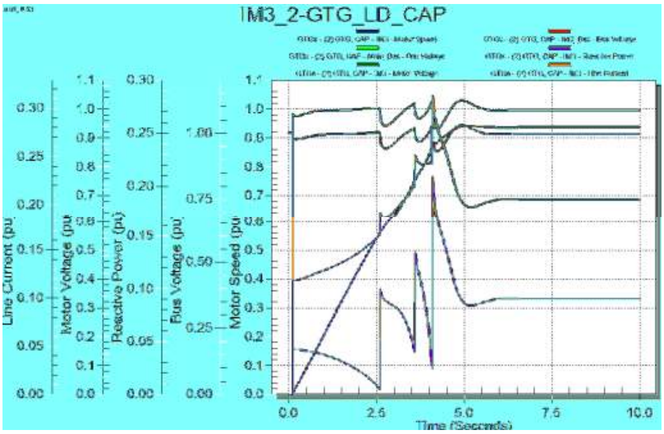
- Problems:
  - Multiple steps required
  - Overvoltages
  - Special control (motor speed)
  - Not suited for Islanded systems





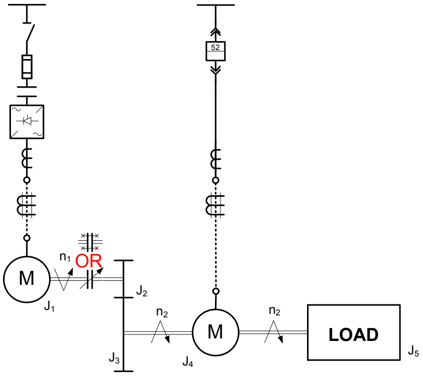
Motor Starting

- Problems
  - (3) steps (i.e. 3x CB)



Motor Starting

- Pony Motor (not Jacking Motor)
  - One Line Representation



Motor Starting - Comparison

Table - Motors Starting Methods / Comparison

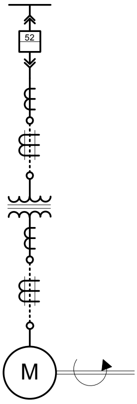
Item #	Train Starting Method	Stiff Network	Weak Network	Load with High Breakaway Troque	High Torsional Stresses Not Allowed - Fast Acceleration	System Issues	Locked Rotor		Maximum		Cost [pu]	Motor Starts Per Hour	Notes
							Line Inrush [pu]	Voltage [pu]	Value [pu]	Duration [sec]			
1	FVNR / DOL	Prefered, if voltage drop excessive use 2,3,7,8	Results in unaceptable voltage drop	Prefereable; otherwise use 4, 5, 6	Not recomended		6.0	0.8	6.0	3 - 10	1.0	1 - 2	
2	Reactor / Resitor Start	Only is FVNR is not acceptable	Evaluate; if negative use 4, 5, 6	Not recommended	Prefered		3.5	.85	3.5	5 - 12	1.6	1 - 2	0.70 Tap
3	RVAT	Only is FVNR is not acceptable	Evaluate; if negative use 4, 5, 6	Not recommended	Prefered		2.5	0.9	2.5	5 - 12	1.4	1 - 2	0.70 Tap
4	Shunt Capacitor	Not recomended	Prefered on cost basis	Capacitors used as network support may allow a FVNR start	Not recommended	Resonance, back-to-back switching, overexcitation/ stability	2.2	0.89	4.5	1 - 2	2.5	1 - 2	50 %kVAR Correction
5	Wound Rotor	If soft start required	Guaranteed start	No problems, guaranteed start	Prefered		1.0	0.97	3.0	1 - 2	2.0	1 - 2	100% LRT limit
6	Pony Motor	Not recomended	Use if capacitor start is unsucesfull	NO starting problem for unloaded driven eqp.	Not recommended		1.2	0.96	2.0	10-300	1.8	Multiple	
7	RVSS	If soft start required	Evaluate; if negative use 4, 5, 6	Not recommended	Prefered		3.5	0.8	3-5	10-30	1.4	1 - 2	I(limit)=250%
8	Captive Transfromer	If voltage drop in the utility network needs to be minimized	Evaluate; if negative use 4, 5, 6	Not recommended	Use if voltage stepdown function is required								
9	Frequency/Voltage Strt PWM ASD	If soft start required	Guaranteed start	No problems, guaranteed start	Prefered	SSR, Resonance	1.3	0.98	2.0	10-30	2-5	Multiple	24-48 pules
10	Frequency/Voltage Strt LCI ASD	If soft start required	Guaranteed start	No problems, guaranteed start	Prefered	SSR, Resonance	1.3	0.98	2.0	10-30	2-5	Multiple	
11	Frequency/Voltage Strt Isolated Bus	If soft start required	Guaranteed start	No problems, guaranteed start	Prefered	Special							V/f=const, Special Consideration
12	Synchronious Motor					Stability	4.5	0.9	2.1	2-5	1.6	1 - 2	Brushless Type

Notes:

Cost and system paramters based on 10kHp motor selection needed for mechanical train.

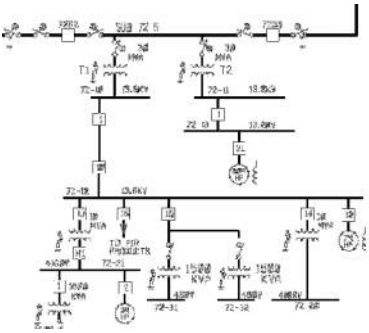
Motor Starting

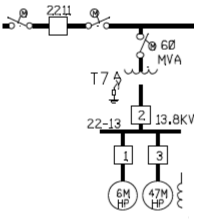
- Captive Transformer Starter
  - One Line Representation



Motor Starting

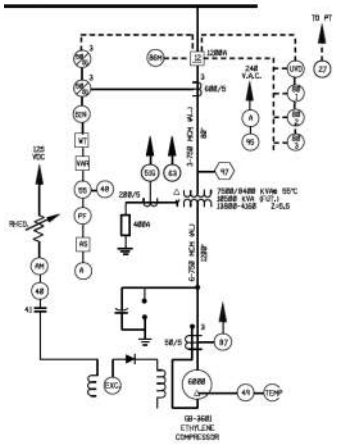
- Captive Transformer Starter
  - Actual One Lines





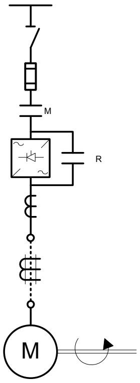
Motor Starting

- Captive Transformer Starter
  - Actual One Lines



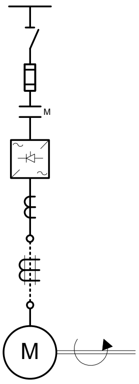
Motor Starting

- Reduce Voltage Solid State Starter with V/f=const, Thermal Limitation

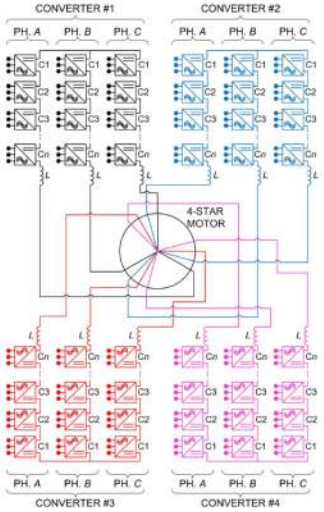


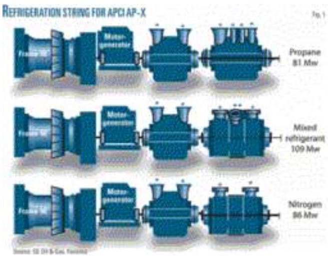
Motor Starting

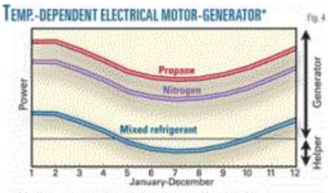
- Variable Frequency Drive Starting and Control



Motor Starting – Special Methods







*Used for power regeneration and/or helper for three refrigeration strings.
Source: Qatargas II

Motor Starting

- Variable Generator / Isolated Bus Motor Starting
  - Principle: use turbine/engine together with generator as a “VFD” starter.

Starting Large AC Motors
Day 2

For

IEEE Houston Section – CED Seminar

By:

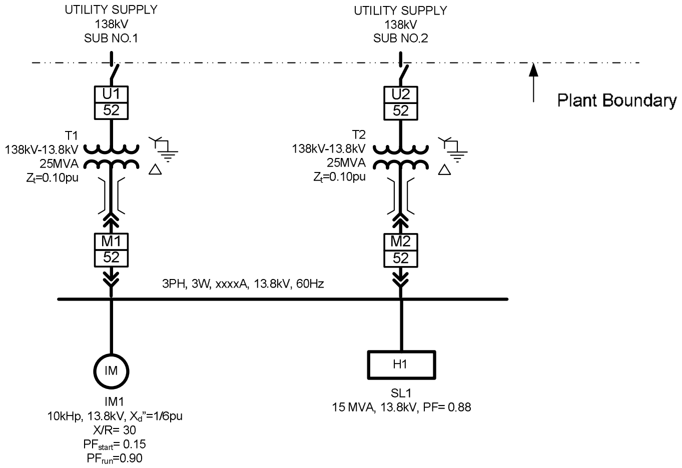
Roy Cosse, P.E.
Robert Spiewak, P.E.

Presentation Code: 214

March 22-23, 2016

Motor Starting

- Typical Application - DOL

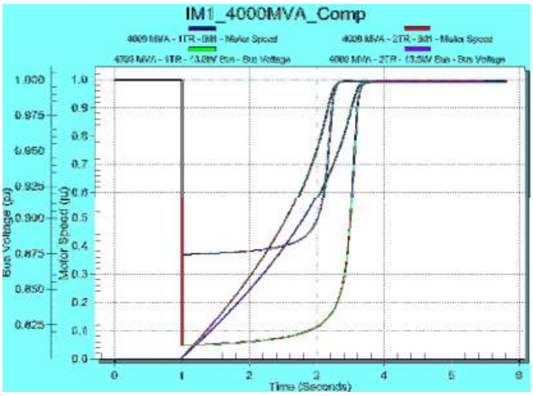


Motor Starting

- Typical Application – Cont.
  - Condition 1 – S_{sc}=4000 MVA, X/R=5
    - o Both T's On-Line
    - o One T On-Line
  - Condition 2 – S_{sc}=1000 MVA, X/R=5
    - o Both T's On-Line
    - o One T On-Line

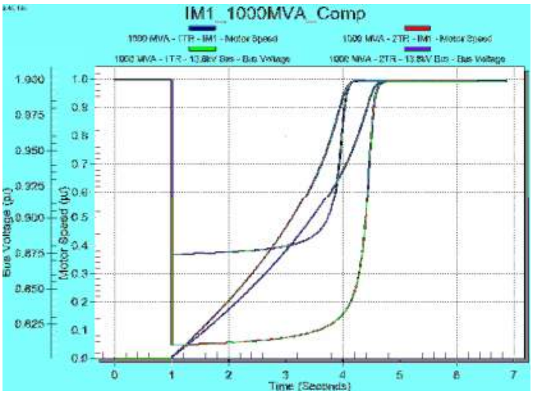
Motor Starting

- Typical Application – Cont.
  - Condition 1 – S_{sc}=4000 MVA, X/R=5
    - o Both TRs On-Line
    - o One TR On-Line



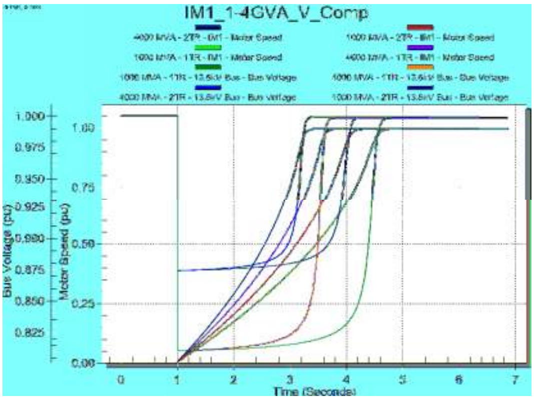
Motor Starting

- Typical Application – Cont.
  - Condition 2 – S_{sc}=1000 MVA, X/R=5
    - o Both TR's On-Line
    - o One TR On-Line



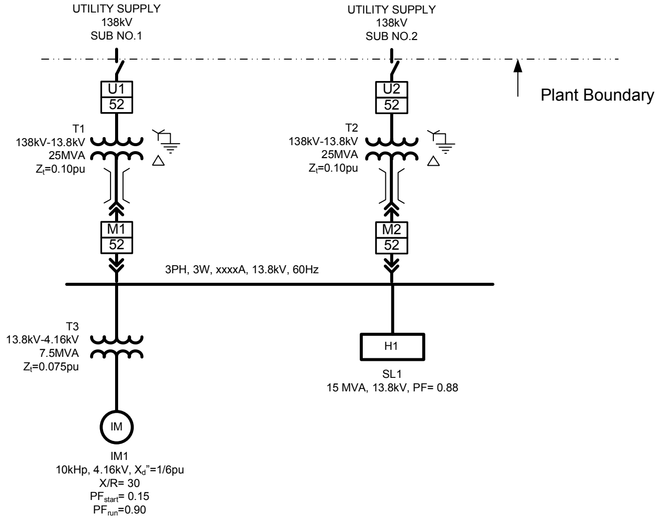
Motor Starting

- Typical Application – Comparison



Motor Starting

- Captive Transformer

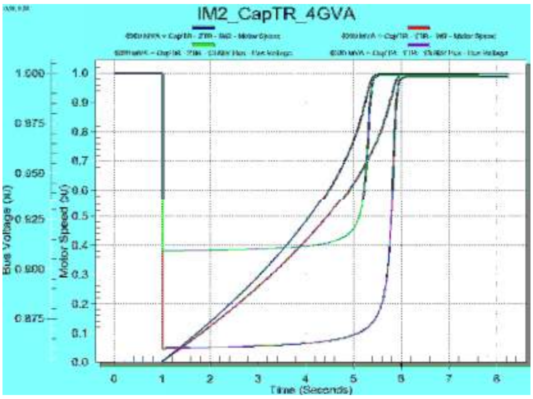


Motor Starting

- Captive Transformer – Cont.
  - Condition 1 – S_{sc}=4000 MVA, X/R=5
    - o Both T's On-Line
    - o One T On-Line
  - Condition 2 – S_{sc}=1000 MVA, X/R=5
    - o Both T's On-Line
    - o One T On-Line
  - Condition 3 - Change voltage from 13.8 kV to 13.2 kV

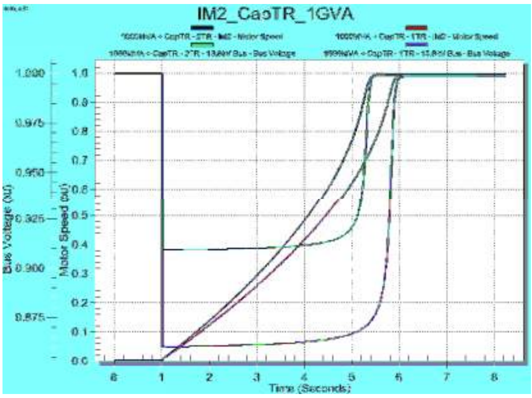
Motor Starting

- Captive Transformer – Cont.
  - Condition 1 – S_{sc}=4000 MVA, X/R=5
    - o Both T's On-Line
    - o One T On-Line



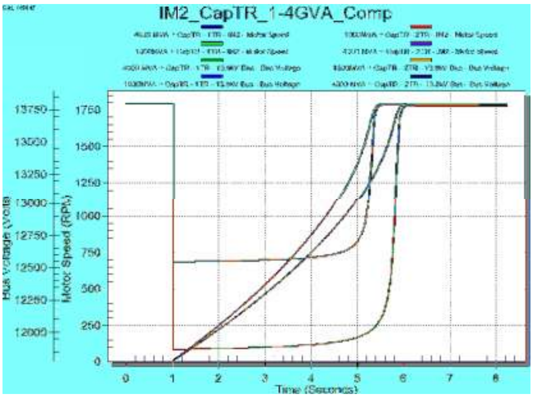
Motor Starting

- Captive Transformer – Cont.
  - Condition 2 – S_{sc}=1000 MVA, X/R=5
    - o Both T’s On-Line
    - o One T On-Line



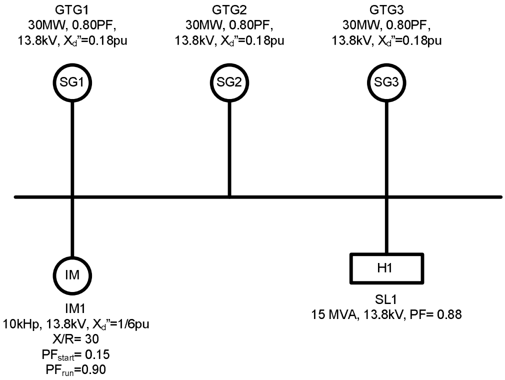
Motor Starting

- Captive Transformer – Comparison



Motor Starting

- Islanded Systems

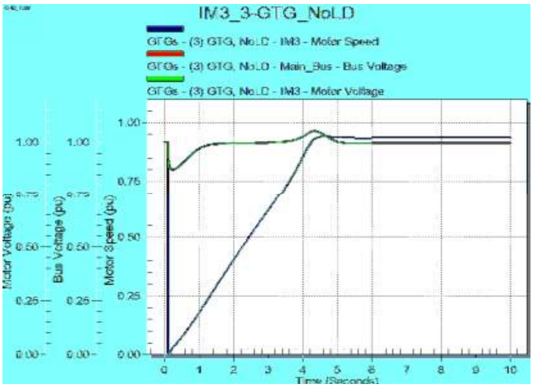


Motor Starting

- Typical Application – Cont.
  - Condition 1 (TMS)
    - Large IM start only, no other loads
    - (3) GTGs On-Line
  - Condition 2 (TMS)
    - Large IM start only, no other loads
    - (2) GTGs On-Line
  - Condition 3 (TMS)
    - Large IM start only with other loads
    - (2) GTGs On-Line
  - Condition 4 (TMS/ISIM)
    - Motor inrush 6x FLA
    - Motor inrush 3x FLA

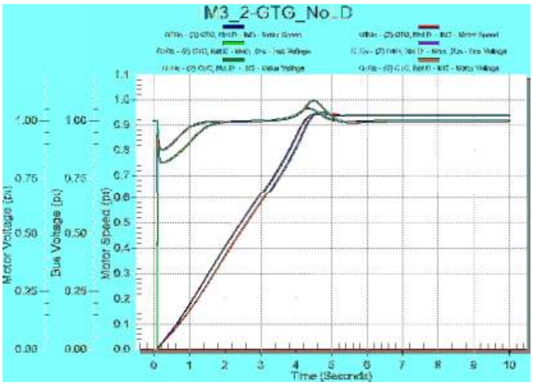
Motor Starting

- Condition 1
  - Large IM start only, no other loads
  - (3) GTGs On-Line



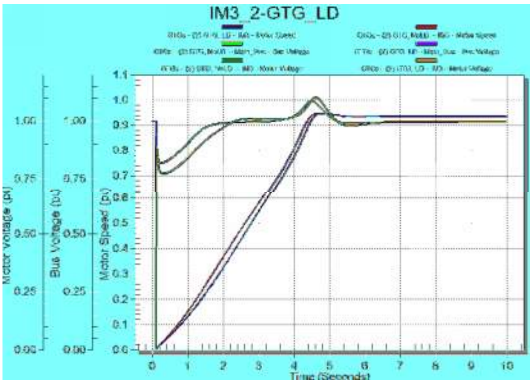
Motor Starting

- Condition 2
  - Large IM start only, no other loads
  - (2) GTGs On-Line



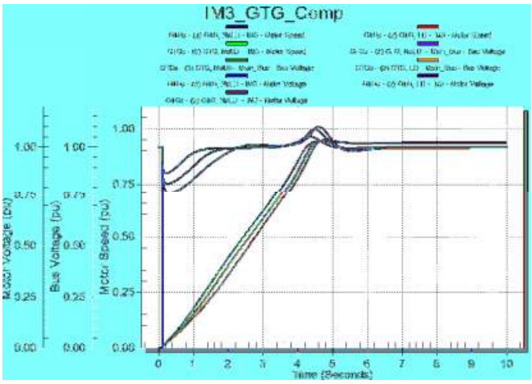
Motor Starting

- Condition 3
  - Large IM start only with other loads
  - (2) GTGs On-Line



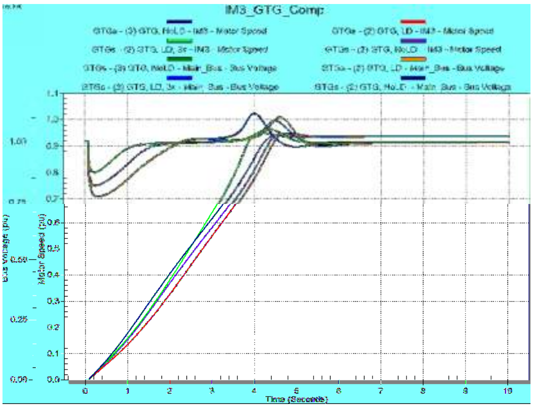
Motor Starting

- GTG Condition – Comparison



Motor Starting

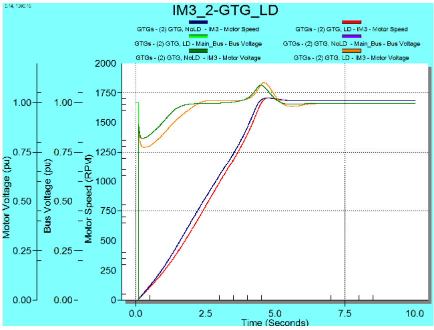
- Condition 4
  - Motor inrush 6x FLA
  - Motor inrush 3x FLA

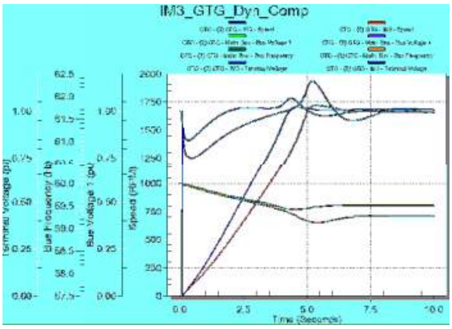


Motor Starting

- Comparison – TMS vs. ISIM

Transient Motor Starting **Dynamic Motor Starting**

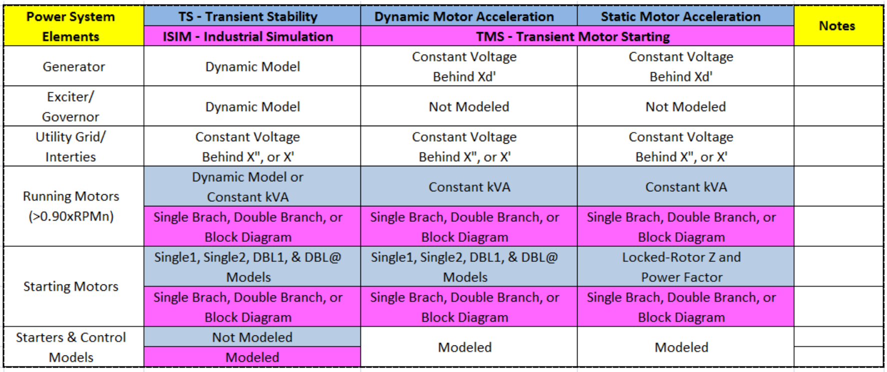




Motor Starting

- Comparison -

System Element Models vs. Calculation Method

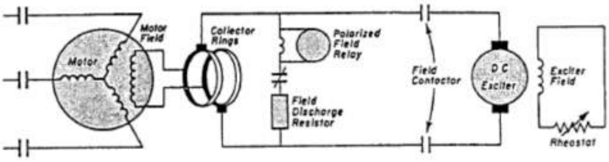


Power System Elements	TS - Transient Stability ISIM - Industrial Simulation	Dynamic Motor Acceleration TMS - Transient Motor Starting	Static Motor Acceleration	Notes
Generator	Dynamic Model	Constant Voltage Behind Xd'	Constant Voltage Behind Xd'	
Exciter/ Governor	Dynamic Model	Not Modeled	Not Modeled	
Utility Grid/ Interties	Constant Voltage Behind X", or X'	Constant Voltage Behind X", or X'	Constant Voltage Behind X", or X'	
Running Motors (>0.90xRPMn)	Dynamic Model or Constant kVA	Constant kVA	Constant kVA	
	Single Brach, Double Branch, or Block Diagram	Single Brach, Double Branch, or Block Diagram	Single Brach, Double Branch, or Block Diagram	
Starting Motors	Single1, Single2, DBL1, & DBL@ Models	Single1, Single2, DBL1, & DBL@ Models	Locked-Rotor Z and Power Factor	
	Single Brach, Double Branch, or Block Diagram	Single Brach, Double Branch, or Block Diagram	Single Brach, Double Branch, or Block Diagram	
Starters & Control Models	Not Modeled	Modeled	Modeled	
	Modeled			

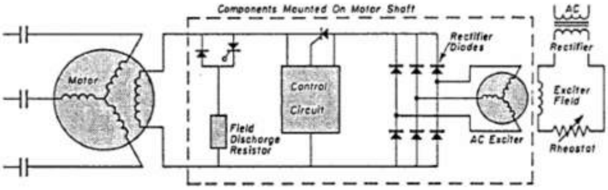
Synchronous Motor

Starting Methods

Synchronous Motor Starting

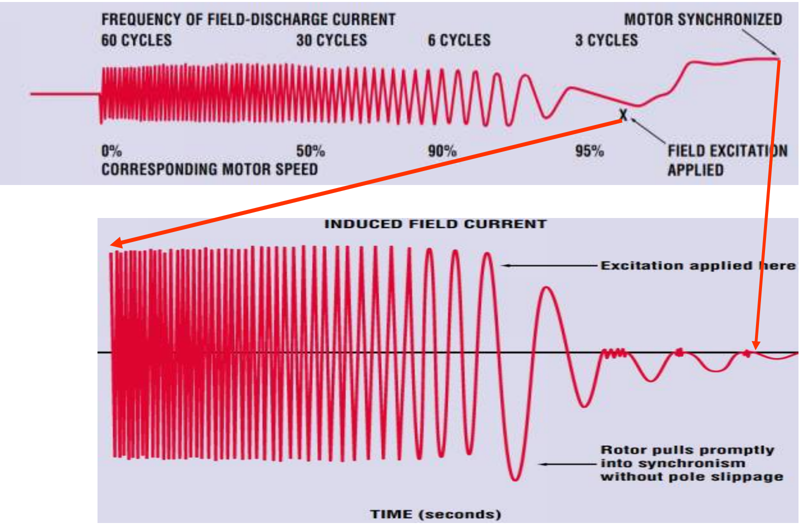


BRUSH-TYPE SYNCHRONOUS MOTOR

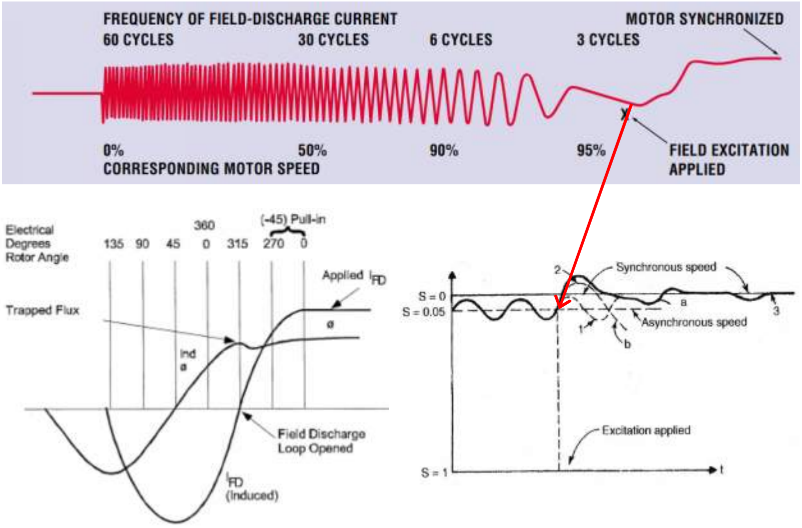


BRUSHLESS-TYPE SYNCHRONOUS MOTOR

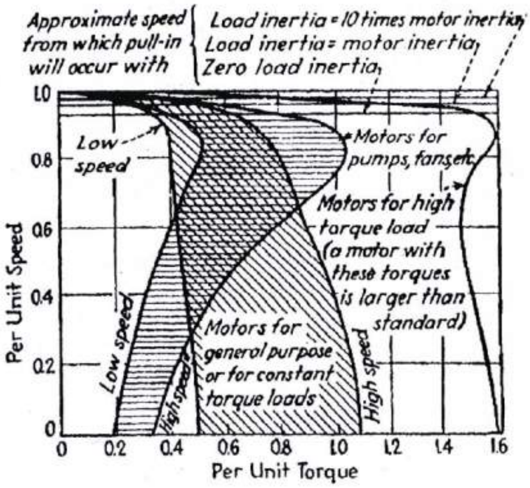
Synchronous Motor Starting



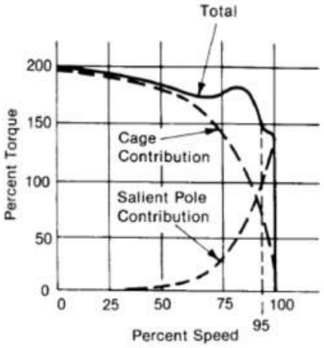
Synchronous Motor Starting



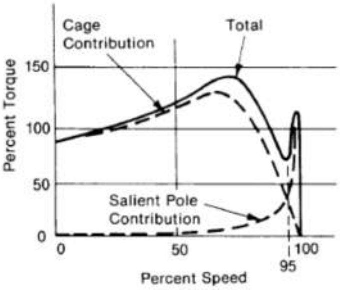
Synchronous Motor Starting



Synchronous Motor Starting



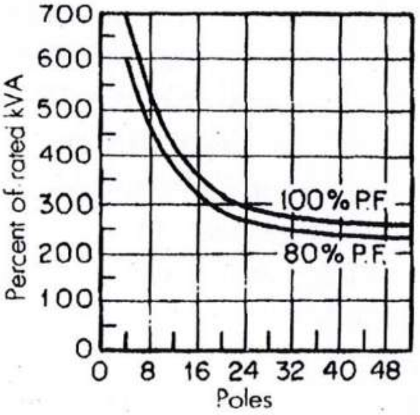
High-Starting Torque



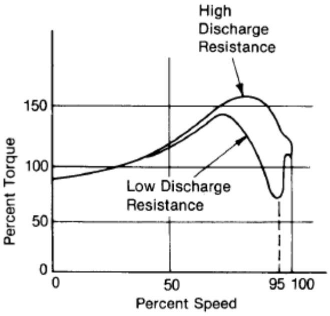
Medium-Starting Torque

Synchronous Motor Starting

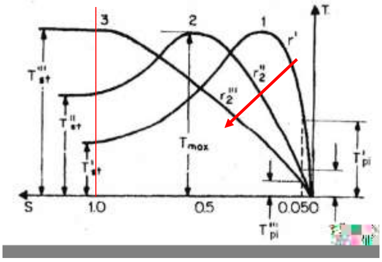
- Approximate starting torque in kVA of SM



Synchronous Motor Starting



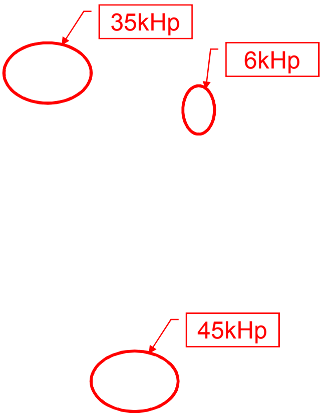
Starting Torque Control via Discharge Resistor



Starting and Pull-In Torque control by resistivity of damper winding material

Synchronous Motor Starting

- Example of damper and field winding interaction



35kHp

6kHp

45kHp

Special Consideration

Special Consideration

- Harmonic Flux

Special Consideration

- Harmonic Torques

Special Consideration

- Typical Slot Design

Special Consideration

- Typical Slot Design

Special Consideration

- Others:
  - Number of starts (or restarts)
  - Process special requirements vs. thermal lockout
  - System stability
  - System harmonic resonances
  - System sub-synchronous resonance

Calculations, Data, Simulation, Applications

Calculations, Simulation, Applications

Software

- ETAP, SKM/PTW
  - Sufficient for DOL starting and reduce voltage discrete calculations; not applicable for RVSS starters analysis
- SPICE, MATLAB, EMTP-ATP
  - Applicable for motor starting analysis with control loops considerations, can predict waveforms and effect on power system
- Custom Software
  - Write own software utilizing Compilers or high level language (i.e. Matlab)
- Hand Calculations
  - Utilize MathCad or other mathematical analysis package; must understand electrometrical theory

---

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Calculations

Motor Data

$P_n := 1200 \cdot \mathrm{Hp}$ $\quad f_n := 60 \cdot \mathrm{Hz}$ $\quad f_s := f_n$ $\quad p := 2$

$P_n = 895.2\mathrm{kW}$

$U_n := 4\mathrm{kV}$ $\quad m_{kr} := 1.8$

$PF_n := 0.87$ $\quad n_n := 1789 \cdot \mathrm{RPM}$

$\eta_n := 0.9595$

$i_r := 5.0$

$m_r := 0.7$

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Calculations

Nominal Parameters

$$I_n := \frac{P_n}{\eta_n \cdot \sqrt{3} \cdot U_n \cdot PF_n} \qquad I_n = 154.79\text{A}$$

$$T_n := \frac{P_n}{\frac{\pi \cdot n_n}{30}} \qquad T_n = 4778.38\text{N} \cdot \text{m} \qquad T_n = 3524.36\text{ft} \cdot \text{lbf}$$

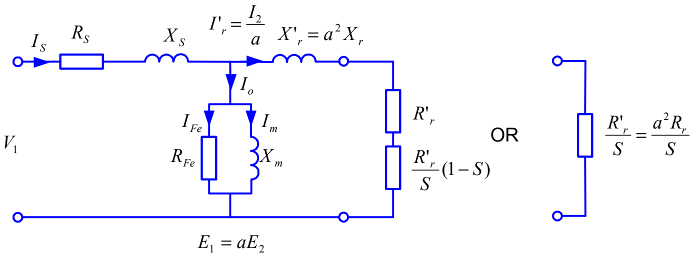
$$\omega_s := \frac{2 \cdot \pi \cdot f_s}{p} \qquad n_s := \frac{60 \cdot f_s}{p} \qquad \omega_s = 188.5\text{s}^{-1} \qquad n_s = 1800\text{RPM}$$

$$s_n := \frac{n_s - n_n}{n_n} \qquad s_n = 0.0061$$

$$Z_z := \frac{U_n}{\sqrt{3} \cdot i_r \cdot I_n} \qquad Z_z = 2.98\Omega$$

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Calculations



Calculations, Simulation, Applications

Equivalent Schematic Parameters – Calculations

Iteration starting parameters:

$R_z := 0.001 \cdot \Omega \qquad X_z := 0.2 \cdot \Omega$

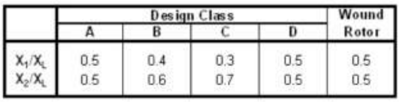
Given

{ From motor equivalent diagram }

$$Z_z = \sqrt{R_z^{\,2} + X_z^{\,2}}$$

$$m_T \cdot T_n = \frac{3}{\omega_s} \cdot \left(\frac{U_n}{\sqrt{3}}\right)^2 \cdot \frac{\frac{R_z}{2}}{R_z^{\,2} + X_z^{\,2}}$$

$$\begin{pmatrix} R_z \\ X_z \end{pmatrix} := \mathrm{Find}(R_z, X_z) \qquad R_z = 0.7\Omega \qquad X_z = 2.9\Omega$$



	Design Class				Wound Rotor
	A	B	C	D	
X_1/X_L	0.5	0.4	0.3	0.5	0.5
X_2/X_L	0.5	0.6	0.7	0.5	0.5

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Calculations

$R_s := R_z \cdot \frac{5}{10}$ $\qquad R_s = 0.35\Omega$

$X_s := X_z \cdot \frac{5}{10}$ $\qquad X_s = 1.45\Omega$

$R'_r := R_s$ $\qquad X'_r := X_s$

$\Delta P_n := P_n \cdot \frac{1 - \eta_n}{\eta_n}$ $\qquad \Delta P_n = 37.79\text{kW}$

$\Delta Pu_n := \frac{3}{2} \cdot I_n^{\,2} \cdot R_z$ $\qquad \Delta Pu_n = 25.22\text{kW}$

$\Delta P_m := 0.01P_n$ $\qquad \Delta P_m = 8.952\text{kW}$

$\Delta P_{fen} := \Delta P_n - \Delta Pu_n - \Delta P_m$ $\qquad \Delta P_{fen} = 3.61\text{kW}$

$R_{fe} := \frac{U_n^{\,2}}{\Delta P_{fen}}$ $\qquad R_{fe} = 4426.97\Omega$

$I_{fe} := \frac{U_n}{\sqrt{3} \cdot R_{fe}}$ $\qquad I_{fe} = 0.52\text{A}$

$I_0 := 20\% \cdot I_n$ $\qquad I_0 = 30.96\text{A}$

$I_m := \sqrt{I_0^{\,2} - I_{fe}^{\,2}}$ $\qquad I_m = 30.95\text{A}$

$X_m := \frac{U_n}{\sqrt{3} \cdot I_m}$ $\qquad X_m = 74.61\Omega$

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Calculations

$Z_s(f) := R_s + \frac{f}{f_n} \cdot j \cdot X_s$

Change "f" only when analysis with VSD

$Z'_r(s,f) := \frac{R'_r}{s} + \frac{f}{f_n} \cdot j \cdot X'_r$

$Z_m := \frac{R_{fe} \cdot X_m \cdot j}{R_{fe} + X_m \cdot j}$

$$Z_m(f) := \frac{\left(\frac{f}{f_n}\right)^{0.7} \cdot R_{fe} \cdot \frac{f}{f_n} \cdot X_m \cdot j}{\left(\frac{f}{f_n}\right)^{0.7} \cdot R_{fe} + \frac{f}{f_n} \cdot X_m \cdot j}$$

$Z(s,f) := Z_s(f) + \frac{Z'_r(s,f) \cdot Z_m(f)}{Z'_r(s,f) + Z_m(f)}$

$U(f) := U_n \cdot \frac{f}{f_n}$

$n(s,f) := \frac{60 \cdot f}{p} \cdot (1 - s)$

$I_s(s,f) := \frac{U(f)}{\sqrt{3} \cdot Z(s,f)}$

$I'_r(s,f) := I_s(s,f) \cdot \frac{Z_m(f)}{Z'_r(s,f) + Z_m(f)}$

$T_e(s,f) := \frac{3 \cdot p}{2 \cdot \pi \cdot f} \cdot \left(\left|I'_r(s,f)\right|\right)^2 \cdot \mathrm{Re}\left(Z'_r(s,f)\right)$

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Calculations

Nominal Slip Calcs

$s := 0.0100$

Given

$T_e(s,f_n) \cdot \frac{\pi \cdot n(s,f_n)}{30} = P_n + \Delta P_m$

$s_n := \mathrm{Find}(s)$ $s_n = 0.0228$

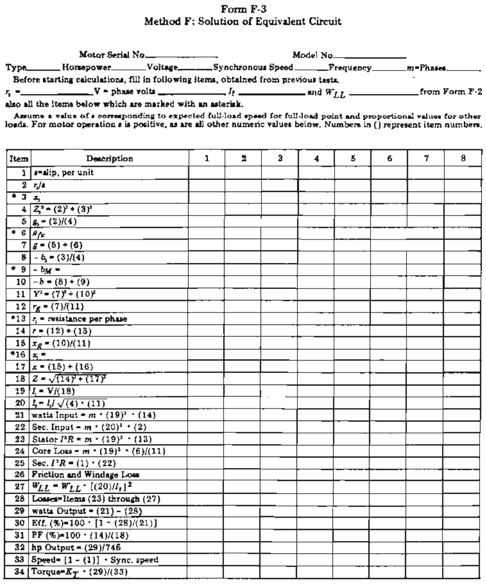
$I_n := \left|I_s(s_n,f_n)\right|$ $I_n = 147.59\mathrm{A}$

$T_n := T_e(s_n,f_n)$ $T_n = 4908.38\mathrm{N} \cdot \mathrm{m}$

Calculations, Simulation, Applications

Equivalent Schematic Parameters –

IEEE 112



Form F-3
Method F: Solution of Equivalent Circuit

Motor Serial No.________ Model No.________

Type______ Horsepower______ Voltage______ Synchronous Speed______ Frequency______ m=Phases______

Before starting calculations, fill in following items, obtained from previous tests.

r_1 =______ V = phase volts ______ I_t ______ and W_{LL} ______ from Form F-2

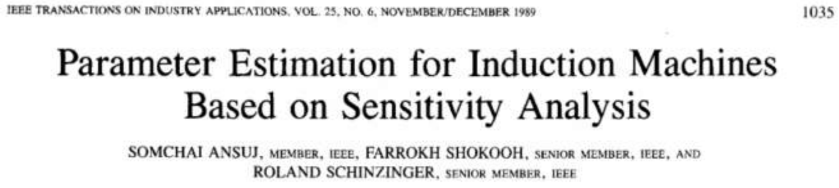
also all the items below which are marked with an asterisk.

Assume a value of s corresponding to expected full-load speed for full-load point and proportional values for other loads. For motor operation s is positive, as are all other numeric values below. Numbers in () represent item numbers.

Item	Description	1	2	3	4	5	6	7	8
1	s=slip, per unit								
2	r_2/s								
* 3	x_2								
4	$Z_2^2 = (2)^2 + (3)^2$								
5	$g_2 = (2)/(4)$								
* 6	g_{fe}								
7	$g = (5) + (6)$								
8	$-b_2 = (3)/(4)$								
* 9	$-b_M =$								
10	$-b = (8) + (9)$								
11	$Y^2 = (7)^2 + (10)^2$								
12	$r_g = (7)/(11)$								
*13	r_1 = resistance per phase								
14	$r = (12) + (13)$								
15	$x_g = (10)/(11)$								
*16	$x_1 =$								
17	$x = (15) + (16)$								
18	$Z = \sqrt{(14)^2 + (17)^2}$								
19	$I_1 = V/(18)$								
20	$I_2 = I_1/\sqrt{(4) \cdot (11)}$								
21	watts Input = $m \cdot (19)^2 \cdot (14)$								
22	Sec. Input = $m \cdot (20)^2 \cdot (2)$								
23	Stator $I^2R = m \cdot (19)^2 \cdot (13)$								
24	Core Loss = $m \cdot (19)^2 \cdot (6)/(11)$								
25	Sec. $I^2R = (1) \cdot (22)$								
26	Friction and Windage Loss								
27	$W_{LL} = W'_{LL} \cdot [(20)/I_t]^2$								
28	Losses=Items (23) through (27)								
29	watts Output = (21) – (28)								
30	Eff. (%)=100 · [1 – (28)/(21)]								
31	PF (%)=100 · (14)/(18)								
32	hp Output = (29)/746								
33	Speed= [1 – (1)] · Sync. speed								
34	Torque=$K_T \cdot (29)/(33)$								

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Sensitivity Calculations



IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 25, NO. 6, NOVEMBER/DECEMBER 1989 1035

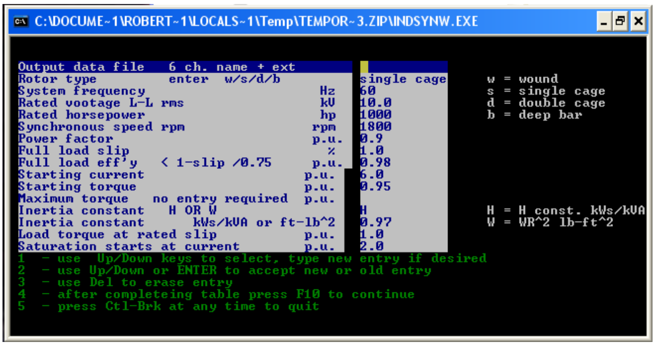
Parameter Estimation for Induction Machines Based on Sensitivity Analysis

SOMCHAI ANSUJ, MEMBER, IEEE, FARROKH SHOKOOH, SENIOR MEMBER, IEEE, AND ROLAND SCHINZINGER, SENIOR MEMBER, IEEE

Basis for ETAP Motor Estimating Calcs

Calculations, Simulation, Applications

Equivalent Schematic Parameters – Sensitivity Calculations

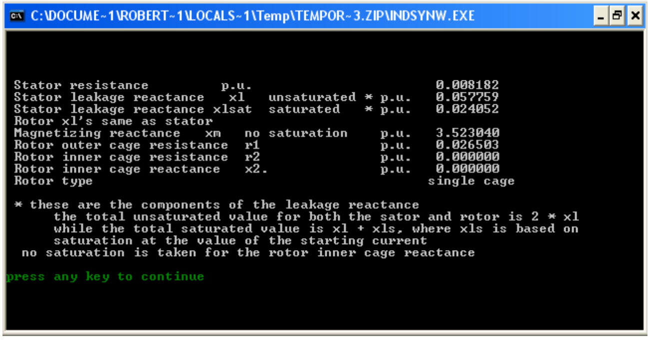


```
Output data file    6 ch. name + ext
Rotor type          enter  w/s/d/b         single cage      w = wound
System frequency                      Hz   60               s = single cage
Rated vootage L-L rms                 kV   10.0             d = double cage
Rated horsepower                      hp   1000             b = deep bar
Synchronous speed rpm                rpm   1800
Power factor                         p.u.  0.9
Full load slip                         %   1.0
Full load eff'y   < 1-slip /0.75     p.u.  0.98
Starting current                    p.u.   6.0
Starting torque                     p.u.   0.95
Maximum torque   no entry required  p.u.
Inertia constant    H OR W                 H                H = H const. kWs/kVA
Inertia constant      kWs/kVA or ft-lb^2   0.97             W = WR^2 lb-ft^2
Load torque at rated slip           p.u.   1.0
Saturation starts at current        p.u.   2.0
1  - use  Up/Down keys to select, type new entry if desired
2  - use Up/Down or ENTER to accept new or old entry
3  - use Del to erase entry
4  - after completeing table press F10 to continue
5  - press Ctl-Brk at any time to quit
```

EMTP-ATP Group Software

Calculations, Simulation, Applications

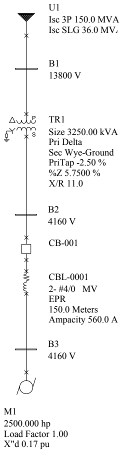
Equivalent Schematic Parameters – Sensitivity Calculations



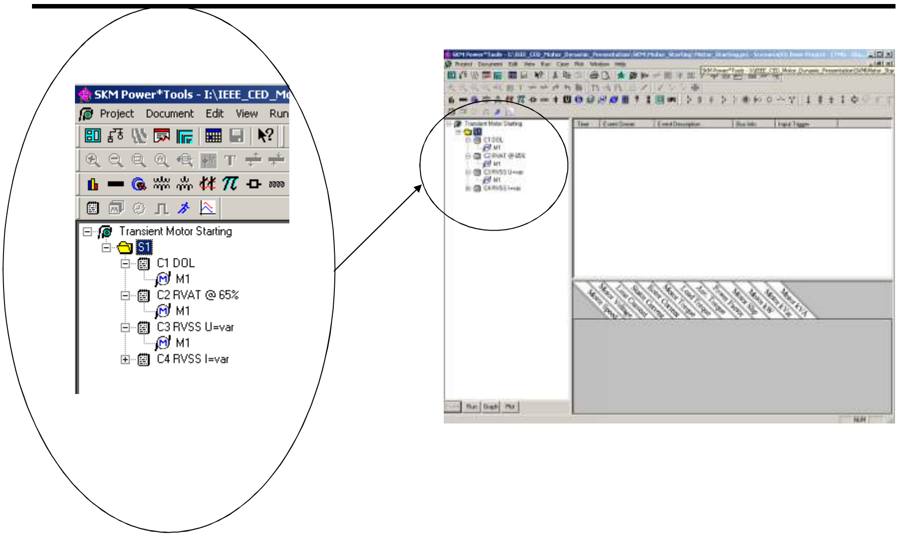
```
 Stator resistance          p.u.                         0.008182
 Stator leakage reactance    xl   unsaturated * p.u.     0.057759
 Stator leakage reactance xlsat   saturated   * p.u.     0.024052
 Rotor xl's same as stator
 Magnetizing reactance   xm   no saturation     p.u.     3.523040
 Rotor outer cage resistance  r1                p.u.     0.026503
 Rotor inner cage resistance  r2                p.u.     0.000000
 Rotor inner cage reactance   x2.               p.u.     0.000000
 Rotor type                                             single cage

 * these are the components of the leakage reactance
      the total unsaturated value for both the sator and rotor is 2 * xl
      while the total saturated value is xl + xls, where xls is based on
      saturation at the value of the starting current
  no saturation is taken for the rotor inner cage reactance

press any key to continue
```

EMTP-ATP Group Software

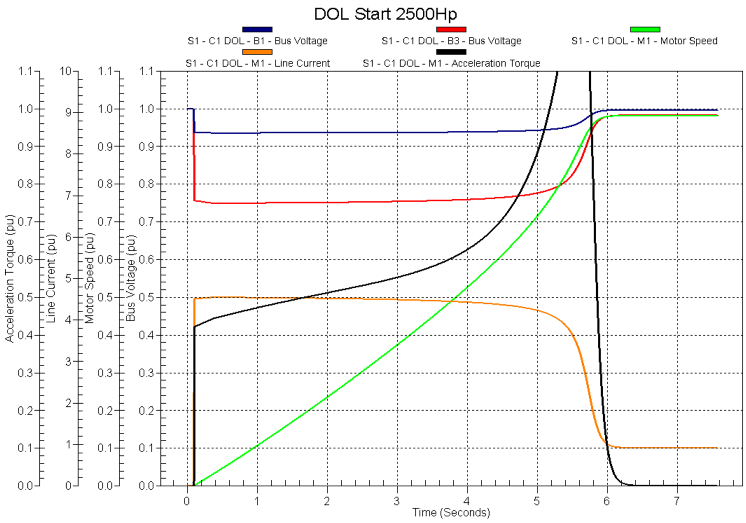
Calculations, Simulation, Applications



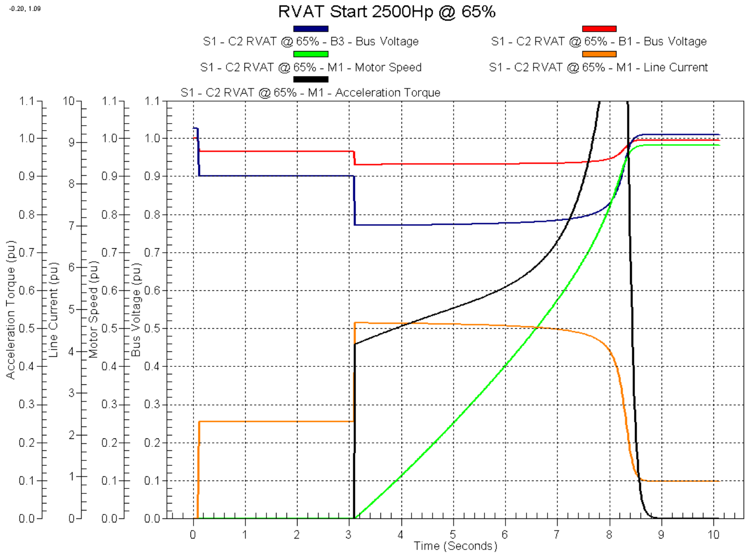
Calculations, Simulation, Applications



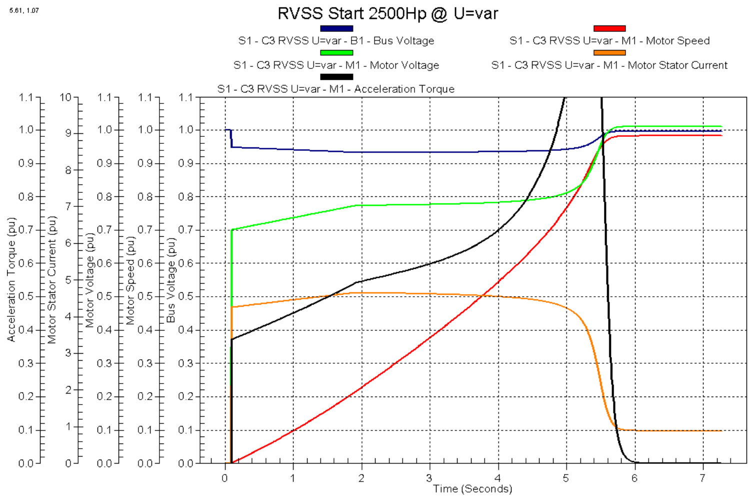
Calculations, Simulation, Applications



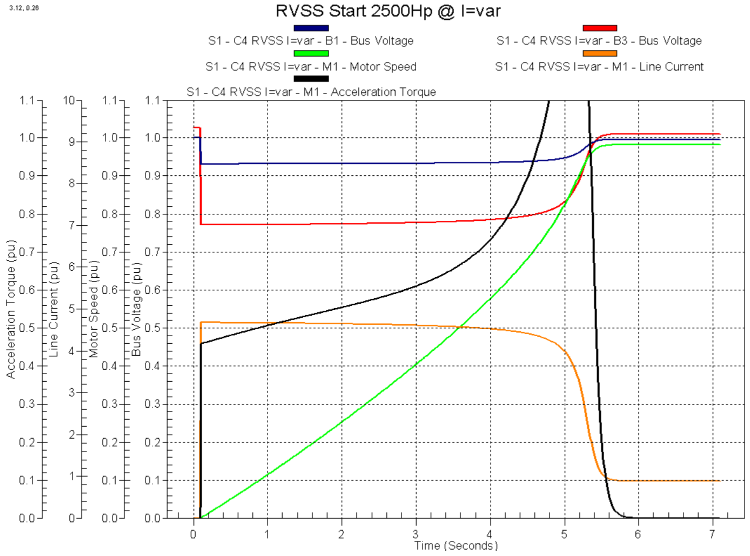
Calculations, Simulation, Applications



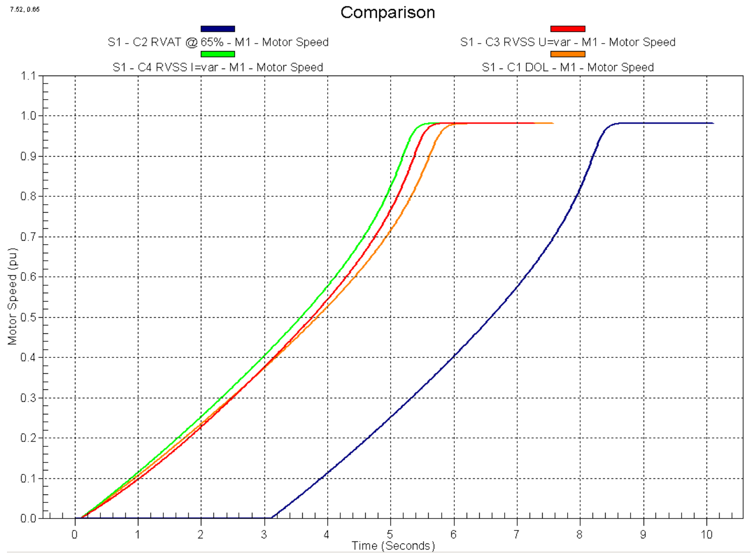
Calculations, Simulation, Applications



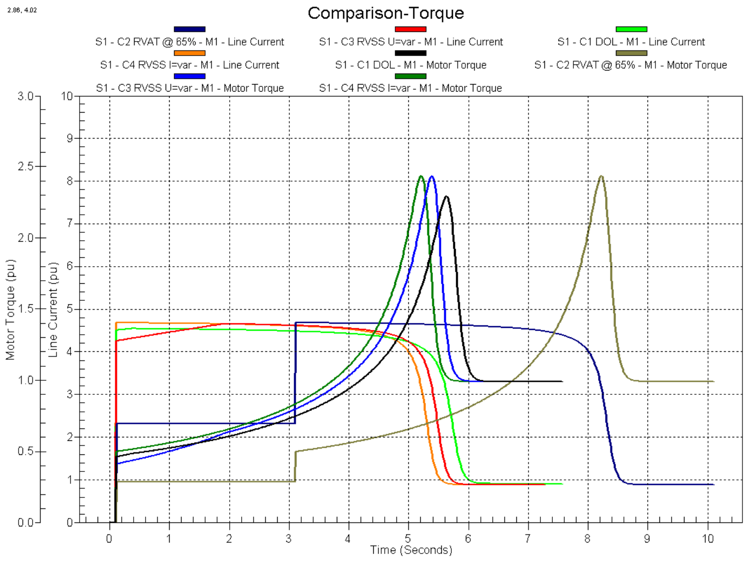
Calculations, Simulation, Applications



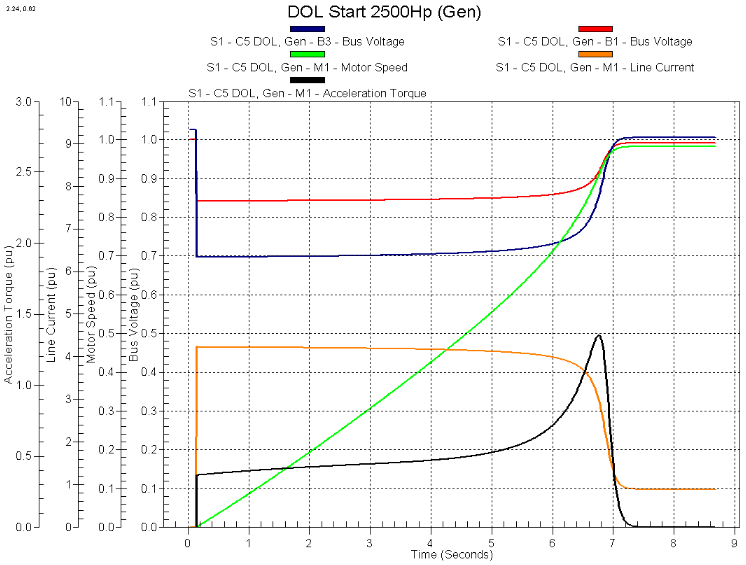
Calculations, Simulation, Applications



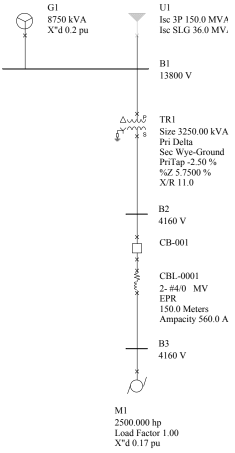
Calculations, Simulation, Applications



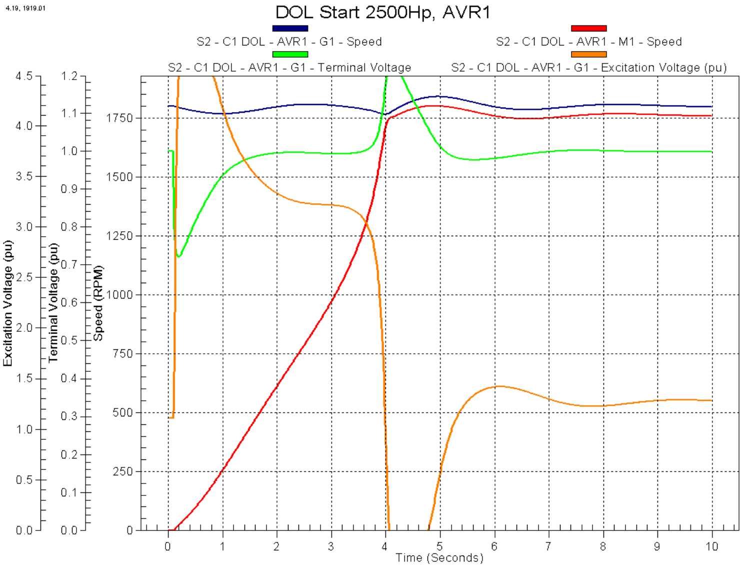
Calculations, Simulation, Applications



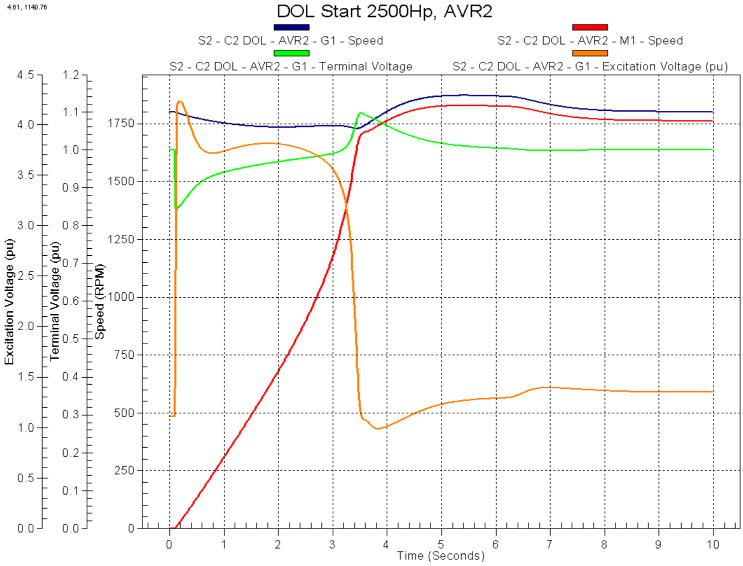
Calculations, Simulation, Applications



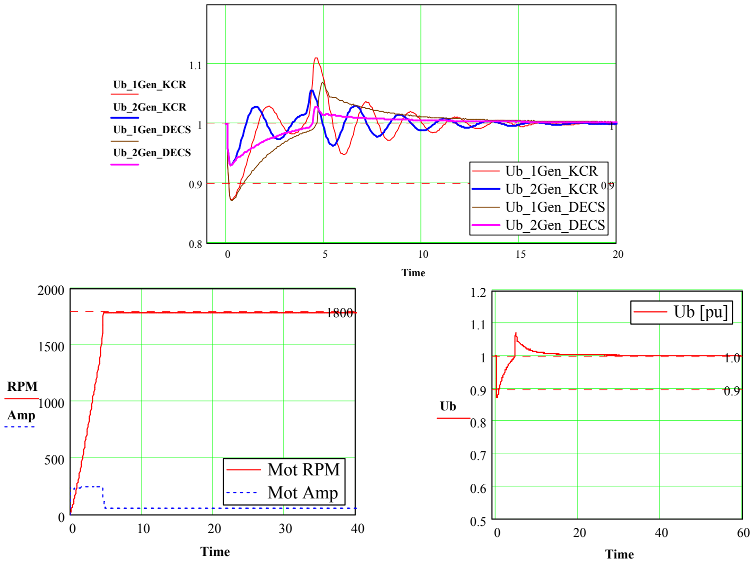
Calculations, Simulation, Applications



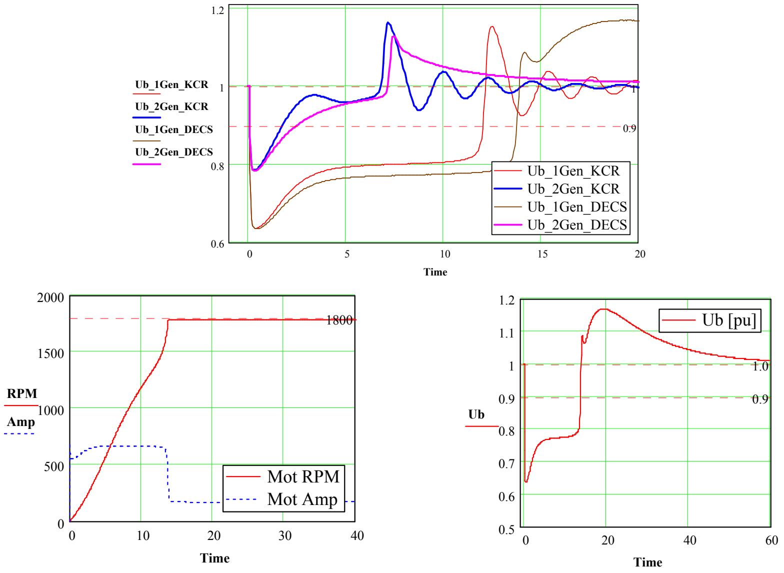
Calculations, Simulation, Applications



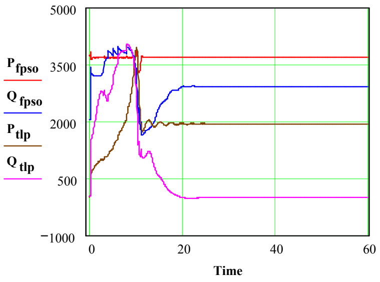
Calculations, Simulation, Applications

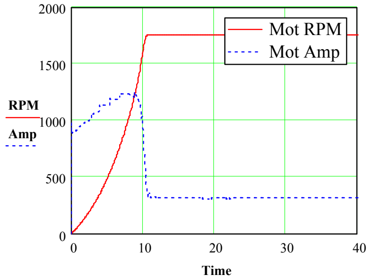


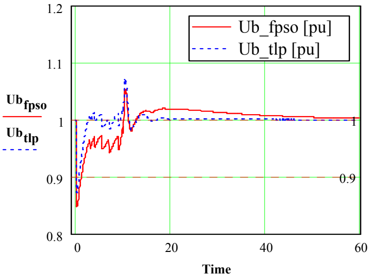
Calculations, Simulation, Applications



Calculations, Simulation, Applications

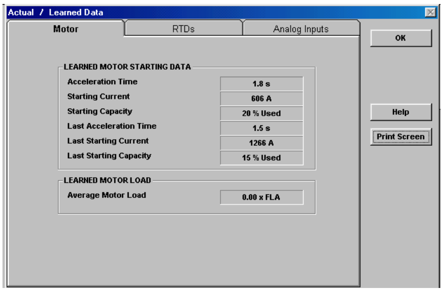






Testing/Protection

Testing/Protection



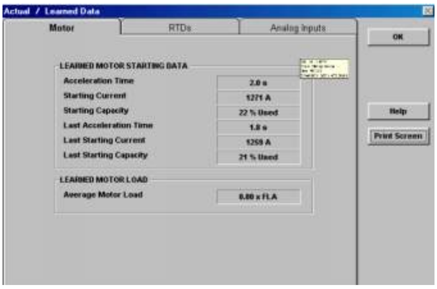
Actual / Learned Data

LEARNED MOTOR STARTING DATA

Acceleration Time	1.8 s
Starting Current	606 A
Starting Capacity	20 % Used
Last Acceleration Time	1.5 s
Last Starting Current	1266 A
Last Starting Capacity	15 % Used

LEARNED MOTOR LOAD

Average Motor Load	0.00 x FLA



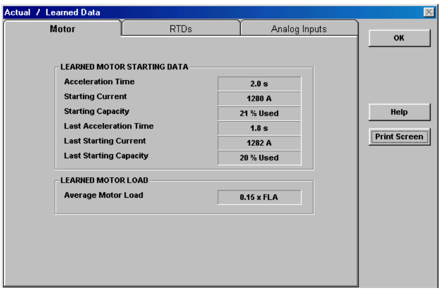
Actual / Learned Data

LEARNED MOTOR STARTING DATA

Acceleration Time	2.0 s
Starting Current	1271 A
Starting Capacity	22 % Used
Last Acceleration Time	1.8 s
Last Starting Current	1259 A
Last Starting Capacity	21 % Used

LEARNED MOTOR LOAD

Average Motor Load	0.00 x FLA



Actual / Learned Data

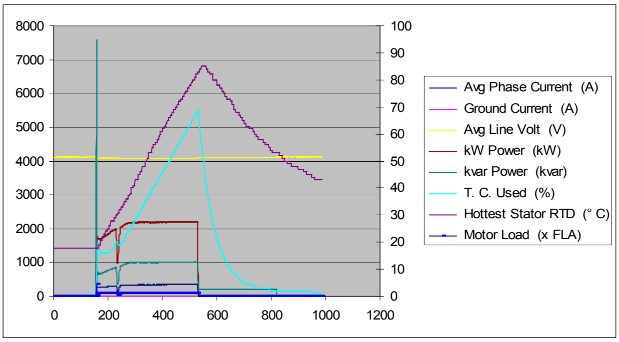
LEARNED MOTOR STARTING DATA

Acceleration Time	2.0 s
Starting Current	1280 A
Starting Capacity	21 % Used
Last Acceleration Time	1.8 s
Last Starting Current	1282 A
Last Starting Capacity	20 % Used

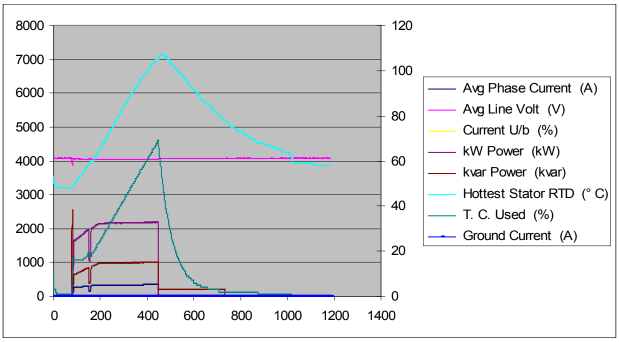
LEARNED MOTOR LOAD

Average Motor Load	0.15 x FLA

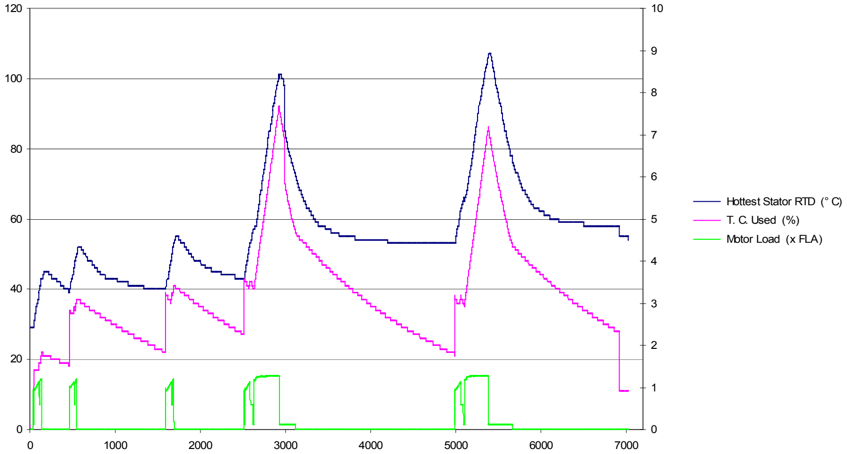
Testing/Protection



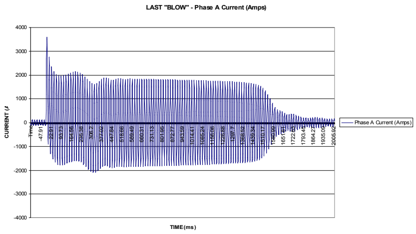
Testing/Protection

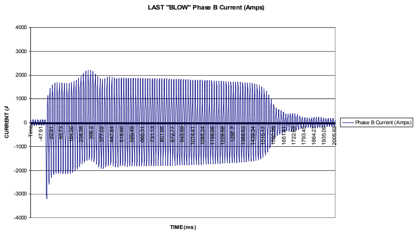


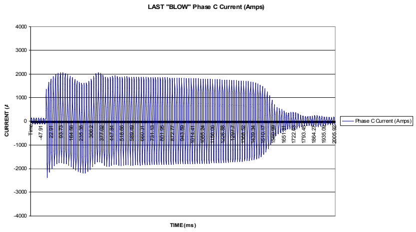
Testing/Protection

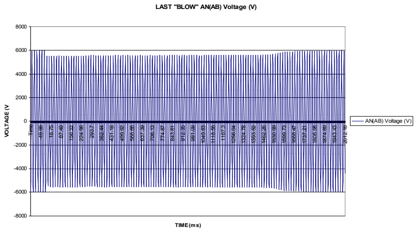


Testing/Protection

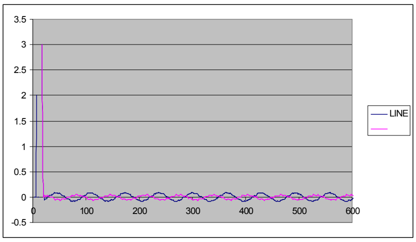

LAST "BLOW" - Phase A Current (Amps)

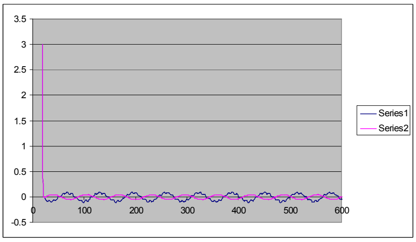

LAST "BLOW" Phase B Current (Amps)

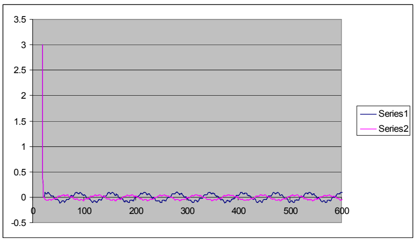

LAST "BLOW" Phase C Current (Amps)


LAST "BLOW" AN(AB) Voltage (V)

Testing/Protection







Questions?

References

[1] A. J. Williams and M. S. Griffith, "Evaluating the Effects of Motor Starting on Industrial and Commercial Power Systems," *Industry Applications, IEEE Transactions on,* vol. IA-14, pp. 292-305, 1978.

[2] D. W. Novotny and T. A. Lipo, *Vector Control and Dynamics of AC Drives*: Clarendon Press, 1996.

[3] P. Vas, *Sensorless Vector and Direct Torque Control*: Oxford University Press, 1998.

[4] W. H. Nichols, F. Bried, R. D. Valentine, and J. E. Harder, "Advances in Capacitor Starting," *Industry Applications, IEEE Transactions on,* vol. IA-20, pp. 56-60, 1984.

[5] P. Vas, *Parameter Estimation, Condition Monitoring, and Diagnosis of Electrical Machines*: Clarendon Press, 1993.

[6] H. Dresig and F. Holzweißig, *Dynamics of Machinery: Theory and Applications*: Springer Berlin Heidelberg, 2010.

[7] E-M, "The ABC's of Synchronous Motors," *E-M Synchronizer,* vol. 200-SYN-42, 1984.

[8] J. R. Smith and M. J. Chen, *Three-phase electrical machine systems: computer simulation*: Research Studies Press, 1993.

[9] J. R. Smith, *Response Analysis of A.C. Electrical Machines: Computer Models and Simulation*: Research Studies Press, 1990.

[10] J. P. Louis, *Control of Synchronous Motors*: Wiley, 2013.

[11] W. Leonhard, *Control of Electrical Drives*: Springer Berlin Heidelberg, 2012.

[12] J. Chiasson, *Modeling and High Performance Control of Electric Machines*: Wiley, 2005.

[13] M. Liwschitz-Garik and C. C. Whipple, *A-C machines*: D. Van Nostrand company, inc., 1946.

[14] A. E. Fitzgerald, C. Kingsley, and S. D. Umans, *Electric Machinery*: McGraw-Hill, 2003.

[15] J. Nevelsteen and H. Aragon, "Starting of large motors-methods and economics," *Industry Applications, IEEE Transactions on,* vol. 25, pp. 1012-1018, 1989.

[16] J. H. Stout, "Capacitor Starting of Large Motors," *Industry Applications, IEEE Transactions on,* vol. IA-14, pp. 209-212, 1978.

[17] J. Bredthauer and N. Struck, "Starting of large medium voltage motors design, protection and safety aspects," in *Petroleum and Chemical Industry Conference, 1994. Record of Conference Papers., Institute of Electrical and Electronics Engineers Incorporated Industry Applications Society 41st Annual*, 1994, pp. 141-151.

[18] K. LeDoux, P. Visser, D. Hulin, and H. Nguyen, "Starting large synchronous motors in weak power systems," in *Petroleum and Chemical Industry Technical Conference (PCIC),*

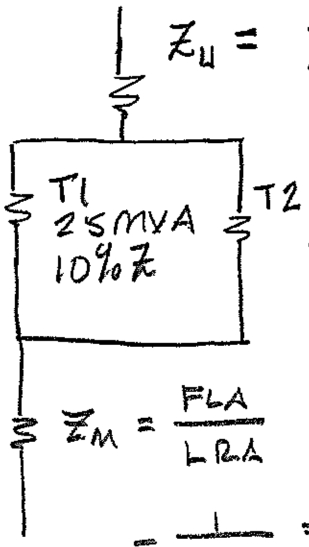
[19] H. E. Koenig and W. A. Blackwell, *Electromechanical system theory*: McGraw-Hill, 1961.

[20] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and I. P. E. Society, *Analysis of electric machinery and drive systems*: IEEE Press,

[21] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and S. Pekarek, *Analysis of Electric Machinery and Drive Systems*: Wiley, 2013.

[22] P. C. Krause, *Analysis of electric machinery*. New York: McGraw-Hill, 1986.

100MVA BASE



$Z_U = \frac{100MVA_{BASE}}{4000MVA} \Rightarrow$ 0.025 puZ

$Z_{T1} \| Z_{T2} = \frac{0.1\times 0.1}{0.1+0.1}$

$= 0.05$ pu Z
AT 25 MVA $_{BASE}$

0.200 puZ

$Z_M = \frac{FLA}{LRA}$

$= \frac{1}{6} = 0.167$ pu Z
AT 9.210 MVA BASE

$\frac{1.813}{2.038}$ puZ
puZ

$MVA = \frac{10KHP \times 0.746 \frac{KW}{HP}}{0.9PF \times 0.9EFF}$

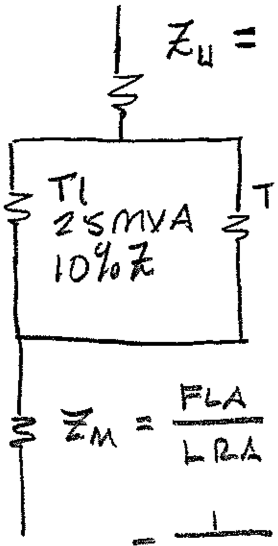
$= 9.210$ MVA

VOLTAGE AT MOTOR TERMINALS
(VOLTAGE DIVIDER)

$\frac{1.813}{2.038} \times 100 = 88.96\%$ V

MOTOR STARTING - DOL
UTILITY 4000MVA $_{SC}$
T1 ONLINE, T2 ONLINE

100 MVA BASE



$$Z_U = \frac{100\,MVA_{BASE}}{4000\,MVA}$$ 0.025 puZ

T2 = OUT OF SERVICE

$$Z_{T1} = 0.10\,puZ$$ AT 25MVA BASE 0.400 puZ

$$Z_M = \frac{FLA}{LRA} = \frac{1}{6} = 0.167\,puZ$$ AT 9.210 MVA BASE

$$\frac{1.813\ puZ}{2.238\ puZ}$$

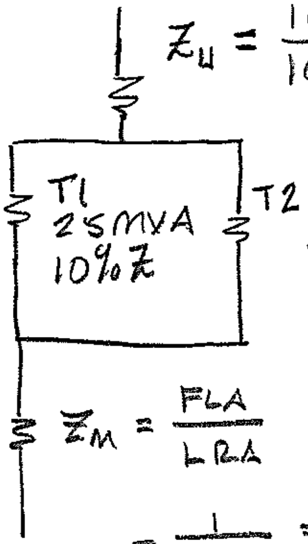
$$MVA = \frac{10KHp \times 0.746\,\frac{KW}{Hp}}{0.9PF \times 0.9EFF} = 9.210\,MVA$$

VOLTAGE AT MOTOR TERMINALS
(VOLTAGE DIVIDER)

$$\frac{1.813}{2.238} \times 100 = 81.01\%V$$

MOTOR STARTING - DOL
UTILITY 4000 MVAsc
T1 ONLINE, T2 OUT OF SERVICE

100 MVA BASE



$Z_U = \frac{100\,MVA_{BASE}}{1000\,MVA}$ 0.100 puZ

$Z_{T1} \parallel Z_{T2} = 5\%$ $25\,MVA_{BASE}$ 0.200 puZ

$Z_M = \frac{FLA}{LRA}$

$= \frac{1}{6} = 0.167$ puZ $9.210\,MVA_{BASE}$ 1.813 puZ

2.113 puZ

$MVA = \frac{10KHp \times 0.746 \frac{KW}{Hp}}{0.9PF \times 0.9EFF}$

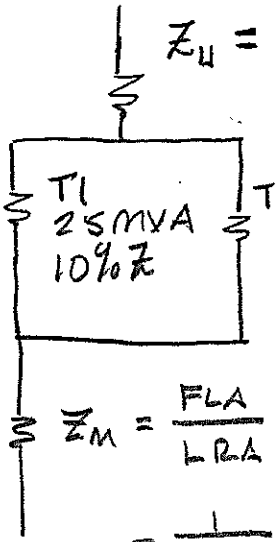
$= 9.210\,MVA$

VOLTAGE AT MOTOR TERMINALS
(VOLTAGE DIVIDER)

$\frac{1.813}{2.113} \times 100 = 85.80\%\,V$

MOTOR STARTING - DOL
UTILITY $1000\,MVA_{SC}$
T1 ONLINE, T2 ONLINE

100 MVA BASE



$Z_U = \frac{100 \text{ MVA}_{BASE}}{1000 \text{ MVA}_{SC}}$ 0,100 pu Z

$Z_{T1} = 0.10$ puZ
25 MVA
0,400 pu Z

$Z_M = \frac{FLA}{LRA}$

$= \frac{1}{6} = 0.167$ pu Z
9.210 MVA

$\text{MVA} = \frac{10\text{K Hp} \times 0.746 \frac{\text{kW}}{\text{Hp}}}{0.9 \text{PF} \times 0.9 \text{EFF}}$

$= 9.210$ MVA

1,813 pu Z

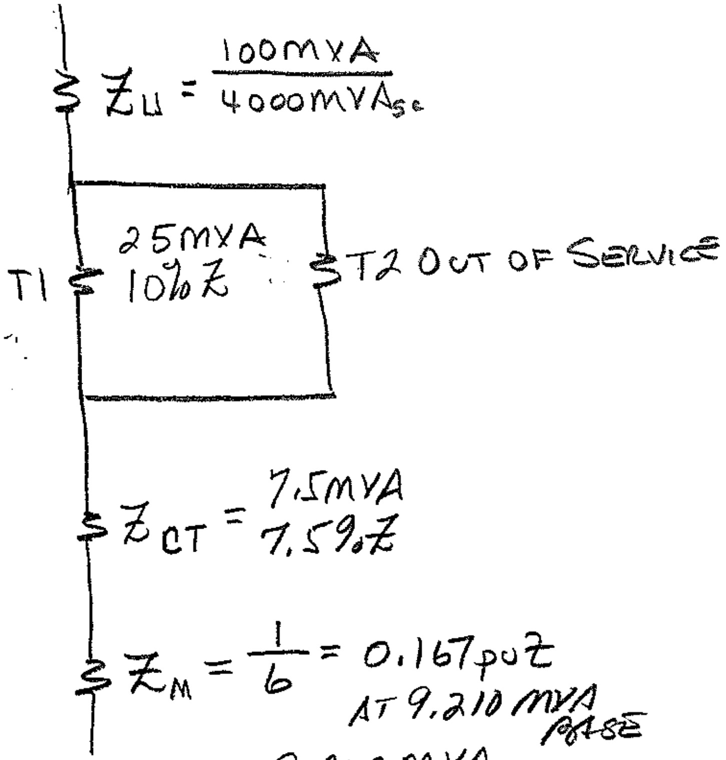
2,313 pu Z

VOLTAGE AT MOTOR TERMINALS
(VOLTAGE DIVIDER)

$\frac{1,813}{2,313} \times 100 = 78,38\% V$

MOTOR STARTING – DOL
UTILITY 1000 MVA$_{SC}$
T1 ONLINE, T2 OUT OF SERVICE

100 MVA BASE



$Z_U = \frac{100\text{MVA}}{4000\text{MVA}_{SC}}$ 0.025 pu Z

T1 0.400 pu Z

$Z_{CT} = \frac{7.5\text{MVA}}{7.5\%Z}$ 1.000 pu Z

$Z_M = \frac{1}{6} = 0.167\text{pu}Z$ AT 9.210 MVA BASE 1.813 pu Z

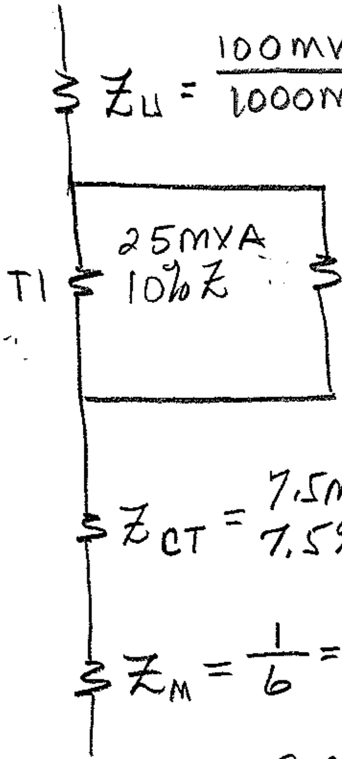
3.238 pu Z

MVA = 9.210 MVA
(SEE PREVIOUS CALC)

VOLTAGE AT MOTOR TERMINALS
(VOLTAGE DIVIDER)

$$\frac{1.813}{3.238} \times 100 = 55.99\%V$$

MOTOR STARTING - CAPTIVE XFMR
UTILITY 4000 MVAsc
T1 ONLINE, T2 OUT OF SERVICE



	100MVA BASE
$Z_U = \frac{100\text{MVA BASE}}{1000\text{MVA}}$	0.100 puZ
25MVA 10%Z	0.400 puZ
$Z_{CT} = \frac{7.5\text{MVA}}{7.5\%Z}$ $\frac{100\text{MVA}}{7.5\text{MVA}} \times 0.075$	1.000 puZ
$Z_M = \frac{1}{6} = 0.167$ puZ AT 9.210 MVA BASE	1.813 puZ
	3.313 puZ

MVA = 9.210 MVA
(SEE PREVIOUS CALC)

VOLTAGE AT MOTOR TERMINALS
(VOLTAGE DIVIDER)

$$\frac{1.813}{3.313} \times 100 = 54.72\%V$$

MOTOR STARTING - CAPTIVE XFMR
UTILITY 1000 MVA$_{SC}$
T1 ONLINE, T2 OUT OF SERVICE

37.5 MVA BASE

$\frac{30MW}{0.8PF} = 37.5MVA$ 0.0833 puZ

$X' = 25\%$ FOR 1GEN

FOR 3GEN'S 25%/3

$Z_{10000HP} = 0.167puZ$ 0.6780 puZ

9.210 MVA

FROM PREVIOUS CALC'S 0.7613 puZ

VOLTAGE AT 13.8kV BUS

$\frac{0.678}{0.7613} \times 100 = 89.06\%V$

WITH 2 GENS 0.125 puZ

10,000HP MOTOR 0.678 puZ

0.803 puZ

$V_{13.8kV\ BUS} = \frac{0.678}{0.803} \times 100 = 84.4\%V$

WITH 1 GEN 0.250 puZ

10,000HP MOTOR 0.678 puZ

0.928 puZ

$V_{13.8kV\ BUS} = \frac{0.678}{0.928} \times 100 = 73.06\%V$

MOTOR STARTING
ISLANDED SYSTEM
3-30MW GENERATORS
MOTOR LRA= 6×FLA

37.5MVA BASE

GENERATOR
37.5MVA
X' = 25%
FOR 3GEN'S 25%/3

0.0833 puZ

$Z_{10,000HP} = \frac{FLA}{LRA} = \frac{1}{3} = 0,333$
FROM PREVIOUS CALC 9.210MVA

1.3558 puZ
1.4391

$V_{13.8KV\ BUS} = \frac{1.3558}{1.4391} \times 100 = 94.21\%V$

WITH 2 GENS
10,000HP

0.1250 puZ
1.3558 puZ
1.4808 puZ

$V_{13.8KV\ BUS} = \frac{1.3558}{1.4808} \times 100 = 91.56\%V$

WITH 1 GEN'S
10,000HP

0.2500 puZ
1.3558 puZ
1.6058 puZ

$V_{13.8KV\ BUS} = \frac{1.3558}{1.6058} \times 100 = 84.43\%V$

MOTOR STARTING
ISLANDED SYSTEM
3-30MW GENERATORS
MOTOR LRA = 3 X FLA

250 KVA BASE

ONE GEN.
250KVA, 480V
$X'_d = 33\%$

0.33 puZ

INDUCTION MOTOR
75HP, 460V
90% EFF.
85% P.F.
P.F. START = 20%
LRA = 6XFLA

0.571 puZ
0.901 puZ

$$KVA = \frac{75HP \times 0.746 \frac{kW}{HP}}{0.90EFF \times 0.85PF}$$

$= 73.1$ KVA WITH $Z = 0.167$

$$V_{480V\ BUS} = \frac{0.571}{0.901} \times 100 = 63.4\%V$$

WITH $X'_d = 17\%$
75HP

0.17 puZ
0.571 puZ
0.741 puZ

$$V_{480V\ BUS} = \frac{0.571}{0.741} \times 100 = 77\%V$$

MOTOR STARTING
DIESEL GENERATOR
250KVA
STANDARD X''_d, "LOW" X''_d