DESIGN OF PROTOTYPE DYNAMIC AC POWER MACHINE WITH EQUIVALENT CIRCUIT MODELING (TORQUE SPEED CURVE OF INDUCTION MOTOR 1,1, KW)

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Abstract

Squirrel cage induction motors are widely used in electric motor drives due to their satisfactory mechanical characteristics (torque, current, overloading) and small dimensions, as well as their low price. When starting an induction motor, a large current is required for magnetizing its core, which results in a low power factor, rotor power losses and a temperature rise in the windings. None of these parameters should reach values beyond certain limits until the motor reaches nominal speed.
The speed of an induction motor 1,1kW is affected very little by fluctuations of voltage. The greater the supply voltage of the motor, the induction motor's speed will increase. The torque values (T_{start}, T_{Smax} and T_{max}) are affected by the value of the motor supply voltage: ($V_{p\text{-}nl}$: 132.8, T_{start1} : 7.4, $T_{S\text{-}max1}$: 0.4, T_{max1} : 9.9) V, ($V_{p\text{-}nl}$: 127.0, T_{start2} : 4.8, $T_{S\text{-}max1}$: 0.3, T_{max1} : 8.4) V and ($V_{p\text{-}nl}$: 121.3, T_{start3} : 3.3, $T_{S\text{-}max3}$: 0.2, T_{max3} : 7.1) V. Stator current ($I_{L\text{-}nl}$; 2.5, 2.2, 1.9) Amp rises gradually on account of the increase in magnetising current (I_m : 2.5, 2.2, 1.9) Amp. The magnetising current required to produce the stator flux. The component of the stator current which provides the ampere-turns balancing the rotor ampere-turns will steadily diminish as the rotor current ($I_{L\text{-}nl}$) decrease with the increase in rotor speed (n_r).

Keywords: induction motor, torque, rotor, stator

1. Parameter Induction Motor Tests

No-Load Test, Current (I_{nl}), voltage (V_{nl}) and power (P_{nl}) are measured at the motor input. The losses in the no-load test are those due to core losses, winding losses, wind age and friction. The slip of the induction motor at no-load is very low. in the rotor branch of the equivalent circuit is very high. The no-load rotor current is then negligible and the rotor branch of the equivalent circuit can be neglected. The approximate equivalent circuit for the no-load test becomes.

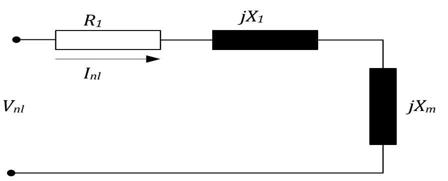


Fig 1. Induction machine equivalent circuit for no-load test

The series resistance in the no-load test equivalent circuit is not simply the stator winding resistance. The no-load rotational losses (windage, friction, and core losses) will also be seen in the no-load measurement. This is why the additional measurement of the DC resistance of the stator windings is required. Given that the rotor current is negligible under no-load conditions, the rotor copper losses are also negligible. Thus, the input power measured in the no-load test is equal to the stator copper losses plus the rotational losses.

$$P_{rot} = P_{nl} - P_{scl} \quad 1)$$

where the stator copper losses are given by

$$P_{scl} = 3\, I_{L-nl}^2\, x\, R_1 \quad 2)$$

The ratio of the no-load voltage to current represents the no-load impedance which, from the no-load equivalent circuit, is

$$Z_{nl} = \frac{V_{P-nl}}{I_{L-nl}} \quad 3)$$

and the blocked rotor reactance sum $X_1 + X_m$ is

$$Z_{nl} = X_1 + X_m \quad 4)$$

Blocked Rotor Test, Current (I_{br}), voltage (V_{br}) and power (P_{br}) are measured at the motor input. The resulting equivalent circuit for the blocked rotor test is shown in the figure below.

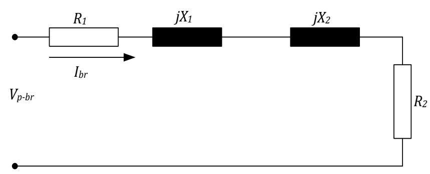


Fig 2. .Induction machine equivalent circuit for blocked rotor test

The slip for the blocked rotor test is unity since the rotor is stationary. The reflected rotor winding resistance is determined from the dissipated power in the blocked rotor test.

$$R_2 = \frac{(P_{br} - 3x\, I_{br}^2 . x R_1)}{3x I_{br}^2} \quad 5)$$

The Reactance rotor is :

$$X_2 = \sqrt{\left(Z_{komp\_br}^2 - (R_1 + R_2)^2\right) - X_1} \quad 6)$$

The power factor is :

$$PF_{br} = \frac{P_{br}}{\left(\sqrt{3}\, x\, V_{L\_r}\, x\, I_{L\_br}\right)} \quad 7)$$

The resistansi ekuivalen is :

$$R_{ekv\_br} = Z_{ekv\_br}\, x\, PF_{br} \quad 8)$$

The reactance ekuivalen is :

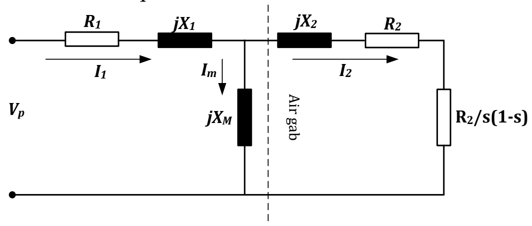
$$X_{ekv\_br} = Z_{ekv\_br} x \sin\left(\cos^{-1}\left(PF_{fl}\right)\right) \quad 9)$$

The Equivalent Impedansi is :

$$Z_{ekv\_br} = \frac{V_{p\_br}}{I_{L\_br}} \quad 10)$$

2. Induction Machine Power

In order to simplify the determination of torque and power equations from the induction machine equivalent circuit, replace the network to the left of the reflected components by a Thevenin equivalent source



The Thevenin voltage (open-circuit voltage) for the stator portion of the equivalent circuit is:

$$V_{th} = \left(\frac{X_m}{(X_1 + X_m)}\right) x\, V_p \quad 11)$$

The thevenin resistance is :

$$R_{th} = \left(\frac{X_m}{(X_1 + X_m)}\right)^2 x\, R_1 \quad 12)$$

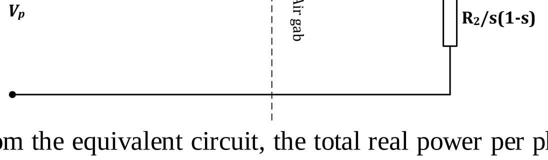
The thevenin reactance is :

$$X_{th} = X_1 \quad 13)$$

The thevenin impedance :

$$Z_{th} = R_{th} + jX_{th} \quad 14)$$

Inserting the Thevenin equivalent source into the induction machine equivalent circuit yields the following equivalent circuit.



From the equivalent circuit, the total real power per phase that crosses the air gap (the air gap power = $P_{air\ gap}$) and is delivered to the rotor is :

$$P_{air\ gap} = I_2^2\left[R_2 + \frac{R_2}{s}\right](1 - s) = I_2^2\frac{R_2}{s} \quad 15)$$

The portion of the air gap power that is dissipated in the form of ohmic loss (copper loss) in the rotor conductors is :

$$P_{ohmic} = I_2^2 R_2 \quad 16)$$

The total mechanical power (P_{mech}) developed internal to the motor is equal to the air gap power minus the ohmic losses in the rotor which gives

$$P_{mech} = P_{air\ gap} - P_{ohmic} \quad 17)$$

The air gap power is :

$$P_{air\ gap} = \omega_s T_{max} \quad 18)$$

The induction machine is an efficient machine when operating at a low value of slip. Conversely, the induction machine is a very inefficient machine when operating at a high value of slip. The overall mechanical power is equal to the power delivered to the shaft of the machine plus losses (windage, friction). The mechanical power (P_{meck}) is equal to torque (N-m) times angular velocity (rad/s).

3. Induction Machine Torque

The torque is therefore inversely proportional to the slip for large values of slip. Between $s = 0$ and $s = 1$, a maximum value of torque is obtained. The maximum value of torque with respect to slip can be obtained by differentiating the torque equation with respect to *s* and setting the derivative equal to zero. The resulting maximum torque (called the *breakdown torque*) is.

$$T_{max} = \frac{\left(3\, {V_{th}}^2\right)}{\left(2\omega_s\left(R_{th} + \sqrt{(R_{th}^2 + (X_{th} + X_2)^2)}\right)\right)} \quad 19)$$

The slip at this maximum torque is :

$$T_{S\,max} = \frac{R_2}{\sqrt{((R_{th})^2 + (X_{th} + X_2)^2)}} \quad 20)$$

And the starting torque is :

$$T_{start} = \frac{\left(3\, {V_{th}}^2\, R_2\right)}{\left(\omega_s\, ((R_{th} + R_2)^2 + (X_{th} + X_2)^2)\right)} \quad 21)$$

4. Induction machine efficiency

The efficiency (η) of an induction machine is the ratio of the output power (P_{out}) to the input power (P_{in}).

$$\eta = \frac{P_{out}}{P_{in}} x100 \quad 22)$$

Where :

The input power (P_{in})

$$P_{in} = 3V_1 I_1 \cos(\theta_v - \theta_i) \quad 23)$$

And

The output power (P_{out})

$$P_{out} = P_{mech} - P_{rot} \quad 24)$$

5. Research Methodology

Testing Locations:
Laboratory of electrical machine and electrical system of electrical engineering department floor 2

Motor specifications :
The three phasa induction motor, Class B, squirrel-cage induction motor. The three-phase stator windings are Δ/Yconnected , 220/380V , 4,3/2,5A , 1,1 KW, 0,67, 1475 rprm, 50Hz

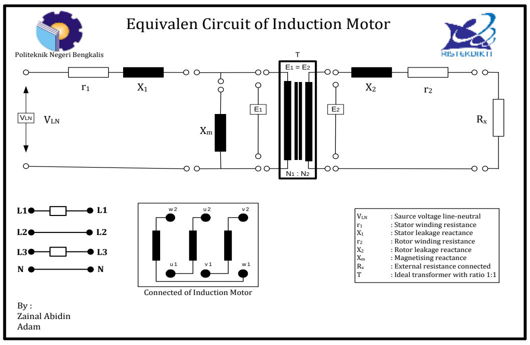


Fig 3. Design of Prototype Dynamic AC Power Machine With Equivalent Circuit Modeling

Table 1. No-load tests motor 1,1 Kw

Parameter	No load Test (nl)		
	Test 1	Test 2	Test 3
V_{L-nl} (V)	230	220	210
I_{L-nl} (A)	2,5	2,2	1,9
P_{nl} (W)	106	101	97

Table 2. Blocked rotor tests motor 1,1 Kw

Parameter	Blocked Rotor test		
	Test 1	Test 2	Test 3
V_{L-br} (V)	64	72	83
I_{L-br} (A)	2,6	2,8	3,0
P_{br} (W)	169	171	183

Rotor resistance (R_1) : 3,5 Ω
Synchronous speed :

$$N_s = \frac{120f}{p} = 1500\ rpm$$

Tabel 3. Parameters of induction motor 1,1 KW

Parameter		Value
Resistance stator	R_1	: 3,5 Ω
Reactance stator	X_1	: 3,22 Ω
Resistance rotor	R_2	: 4,83 Ω
Reactance rotor	X_2	: 8,29 Ω
Magnetising reactance	X_m	: 49,89 Ω
Stator copper losses	P_{scl}	: 65,63 W
Rotational losses	P_{rot}	: 40,37 W

The equivalent circuit for the induction motor is shown below :

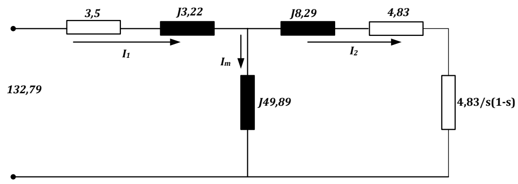


Fig 4. The equivalent circuit of induction motor

Table 4. The results calculation tests 1, 2 and tests 3

Parameter	**Test 1**	**Test 2**	**Test 3**	**SI Unit**
No-load test (nl)				
V_{p-nl}	132,8	127,1	121,3	V
Z_{nl}	53,12	57,74	63,8	Ω
P_{scl}	65,63	50,82	37,9	W
P_{rot}	40,37	50,18	59,1	W
PF_{nl}	0,1064	0,1205	0,1404	
θ_{nl}	$83,89^0$	$83,08^0$	$81,93^0$	
V_m	124,04	119,32	114,6	V
I_m	2,5	2,2	1,9	A
X_m	49,9	54,6	60,9	Ω
X_1	3,2	3,1	2,9	Ω
Blocked rotor test (br)				
Vp-br	36,9	41,6	47,9	V
R_2	4,8	3,8	3,3	Ω
Zekv-br	14,2	14,9	15,9	Ω
PFbr	0,5864	0,4897	0,4243	
θbr	54,100	60,680	64,890	
Rekv-br	8,3	7.3	6,9	Ω
Xekv-br	11,5	12.9	14,5	Ω
X_2	8,3	9.8	11,6	Ω
Thevenin calculation				
V_{th}	124,6	120,2	115,7	V
R_{th}	3,1	3,1	3,2	Ω
X_{th}	3,2	3,1	2,9	Ω
Torque Calculation				
T_{start}	7,4	4,8	3,3	N.m
T_{S-max}	0,4	0,3	0,2	
T_{max}	9,9	8,4	7,1	N.m
Efficiency Calculation				

$P_{air\text{-}gap}$	155,5	131,7	111,6	W
P_{mek}	152,9	129,5	109,7	W
P_{out}	112,5	79,3	50,6	W
P_{in}	183,7	174,9	168	W
η	61,3	45,4	30,1	%

6. Torque Speed Curve Of Induction Motor

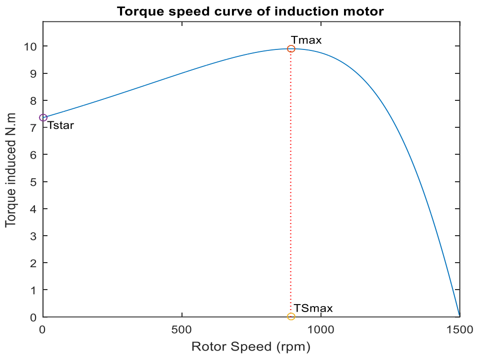


Fig. 5. Torque Speed Curve Test 1

Starting torque (T_{start1}) : 7,36 N.m
Slip for maximum torque ($T_{S\text{-}max1}$) : 0,41
Maximum torque (T_{max1}) : 9,91 N.m
Synchronous speed : 1500 rpm
Phase voltage ($V_{p\text{-}nl}$) : 132,79V

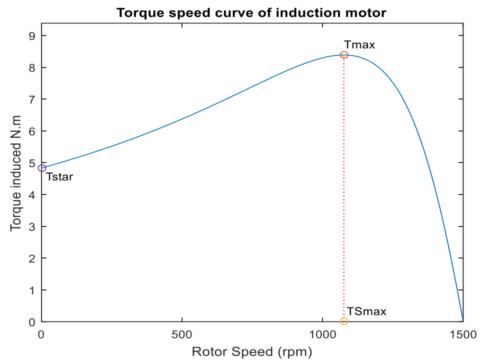


Fig 6. Torque Speed Curve Test 2

Starting torque (T_{start1}) : 4,83 N.m
Slip for maximum torque ($T_{S\text{-}max1}$) : 0,28
Maximum torque (T_{max1}) : 8,39 N.m
Synchronous speed : 1500 rpm
Phase voltage ($V_{p\text{-}nl}$) : 127,02V

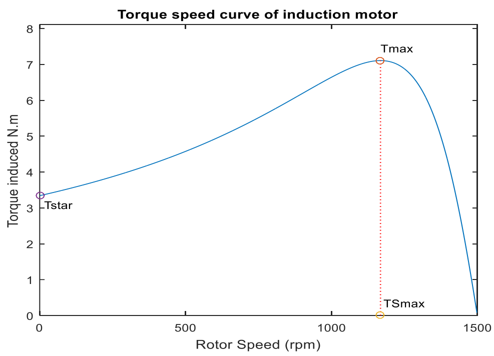


Fig 7. Torque Speed Curve Test 3

Starting torque (T_{start3}) : 3,34 N.m
Slip for maximum torque ($T_{S\text{-}max3}$) : 0,22
Maximum torque (T_{max3}) : 7,11 N.m
Synchronous speed : 1500 rpm
Phase voltage ($V_{p\text{-}nl}$) : 121,25V

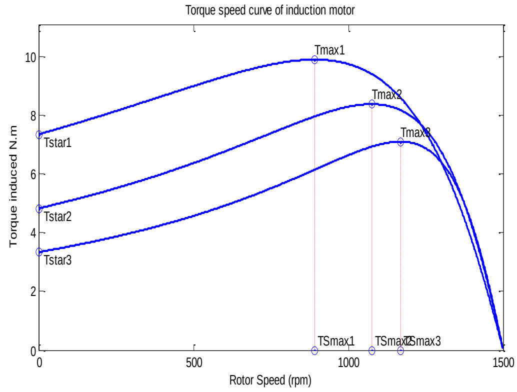


Fig 8. Torque Speed Curve Combined Test 1,2, 3

(T_{start1}, T_{start2}, T_{start3}) : (7,36 , 4,83, 3,34) N.m
($T_{S\text{-}max1}$, $T_{S\text{-}max2}$, $T_{S\text{-}max3}$) : (0,41, 0,28, 0,22)
(T_{max1}, $T_{S\text{-}max2}$, $T_{S\text{-}max3}$) : (9,91 8,39 7,11) N.m
Synchronous speed : 1500 rpm
Phase voltage ($V_{p\text{-}nl}$) : (132,79, 127,02,121,25)V

7. Conclusions

a. The speed of an induction motor is affected very little by fluctuations of voltage (see Fig 5, 6, 7 and 8)

b. The torque values (T_{start}, T_{Smax} and T_{max}) are affected by the value of the motor supply voltage:
($V_{p\text{-}nl}$: 132.8, 127.0, 121.3) V
(T_{start1},T_{start2}, T_{start3} : 7.4, 4.8, 3.3) N.m
($T_{S\text{-}max1}$,$T_{S\text{-}max2}$,$T_{S\text{-}max3}$: 0.4, 0.3, 0.2)
(T_{max1}, $T_{S\text{-}max2}$, $T_{S\text{-}max3}$: 9.9, 8.4, 7.1)N.m

c. Stator current ($I_{L\text{-}nl}$; 2.5, 2.2, 1.9) rises gradually on account of the increase in magnetising current (I_m : 2.5, 2.2, 1.9)A

d. The magnetising component of the stator current becomes larger as the voltage increase. There is a continuous increase in the power factor angle (θ_{nl}) and hence a fall in power factor (PF_{nl}).

e. The stator current (I_1) will increase in proportion to the rotor current (I_2).

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