International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-11 Issue-1, October 2021

Design of Squirrel-Cage Self-Excited 3-phase Induction Generator

Bilal Abdullah Nasir

***Abstract** Due to the wide utilization of a 3-phase, squirrel-cage, self-excitation generator in renewable energy and isolated areas application, the paper deals with detailed design procedure of this type of generator, in a sequence and systematic manner. The design steps are obtained and executed in a Matlab file of the computer program to suit the newly designed constructions and parameters of the generator. In the new construction, the generator can be operated in a stable and saturation region. Due to the similarity in the construction of induction motor and generator, the formulas used in the calculation of equivalent circuit components of an induction motor may be utilized to calculate the parameters of the induction generator. To obtain optimized induction generator parameters and construction dimensions an ant colony algorithm is used to optimize these construction dimensions and generator parameters. The main objective parameters used in this algorithm are the generator efficiency, the excitation-capacitance, winding temperature rise, and minimum generator size is for 5 HP, 400 V, 50 Hz, and star connection generator.*

***Keywords:** Squirrel-Cage Induction Generator, Design Steps, Generator Parameters, Ant Colony Optimization.*

I INTRODUCTION

In recent years, the increasing demand for renewable energy has caused great interest in the development and utilization of wind and micro-hydro-electric power plants. Many papers showed the importance of wind and micro-hydro induction generators' performance analysis, modeling, protection, and control [1-5]. However, there are fewer publications that proposed the design and construction of these types of generators to develop an effective machine for electricity generation, especially in isolated areas and stand-alone generators [6-10]. Two types of secondary windings of the rotor in the induction generator are slip-ring wound rotor and squirrel-cage rotor. Squirrel-cage-type generators are used widely in isolated area applications. The major disadvantages of this type of generator are the low efficiency, high volume size, and low power factor. With a change in the design of the magnetic circuits of this type of generator, the performance can be improved.

Manuscript received on October 11, 2021.
Revised Manuscript received on October 16, 2021.
Manuscript published on October 30, 2021.
***** Correspondence Author
Bilal A. Nasir*, Lecturer, Northern Technical University, Iraq.

These types of generators are used more than the other type of generators due to the ease of operation, construction, maintenance, and low noise. The design of the induction generator for desired and suitable performance must be not restricted by stator and rotor structure. The induction machine is operated as a magnetic circuit and it will be influenced by the magnetic saturation. However, the operation of the squirrel-cage self-excited induction generator becomes stable when the generator workes in the saturation region. Then, the best step to optimize the design of an induction generator is to design a new machine that can carry the saturated magnetizing current and handle the great terminal voltage. The similarity in the construction of induction motor and generator makes it possible to use the design steps of induction motor for the procedure of induction generator. The mathematical formulas and empirical equations used to calculate the equivalent circuit components of the induction motor can be used to calculate the components of the induction generator equivalent circuit. In this paper, a detailed design procedure of squirrel-cage, self-excited induction generator is presented systematically with a design algorithm flow chart, by modifying the classical method of induction motor design. Recently, to solve the optimization requirements an ant colony algorithm has been suggested, which is derived from the foraging behavior of ants to optimize the designed parameters of induction machines [11-13]. In this paper, the ant colony optimization algorithm-based method is used for the optimal design of a squirrel-cage self-excited induction generator. In this method, optimal values of design parameters are determined to maximize the generator efficiency and to minimize the generator excitation capacitance, stator winding temperature, and generator volume.

II DESIGN STEPS

The design procedure of the squirrel-cage, self-excited induction generator involves several steps. The sequence of the design steps can be summarized in a flowchart as shown in figure (1). These steps can be executed as follow:

1- The first step in the design of a squirrel-cage, self-excited induction generator is to define the fixed input specifications data of the generator. For example, the generator has 5 HP output power, 400 V line voltage, 50 Hz, 3-phase supply, and Y-connection type. These data can be states in table (1).

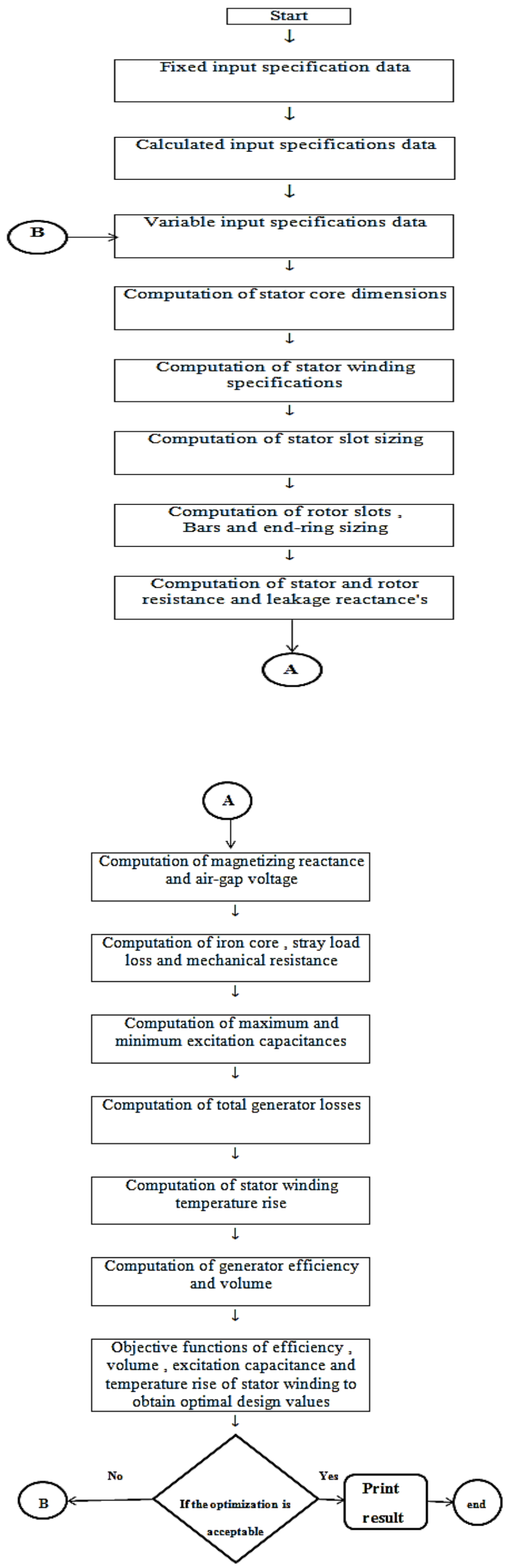

Fig. 1. Flowchart of the design procedure

Table- 1: fixed input specifications

Input parameters of the designed generator	Symbol	Value
Output power	P_{out}	5 HP
Phase voltage	V_{ph}	230 V
Number of phases	m	3
Supply frequency	f_s	50 Hz
Stator-connection	Y	–
Number of magnetic poles	2p	4
Power factor	$\cos(\phi)$	0.9
Speed of operation	N_r	1525 r.p.m
Synchronous speed	N_s	1500 r.p.m
Number of parallel paths	a_p	2
Type of stator winding	layer	1
Efficiency	$\eta\%$	90
Ambient temperature	T_a	25 ℃
The form factor of the sine-wave	K_{ff}	1.1
Stator to rotor mmf factor	K_{mm}	0.9
Mechanical machining factor	K_{ty}	1.7
Saturation factor	K_{st}	0.5
Number of fins in the outer frame	K_{fins}	2.0
Carter coefficient	K_{ca}	1.25
Iron lamination thickness factor	K_{fe}	0.96
Stator winding factor	K_{ws}	0.93
Stator slot filling factor	K_{fil}	0.4
Stator tooth flux density	K_{ts}	1.6 wb/m^2
Stator core flux density	K_{cs}	1.6 wb/m^2
Rotor tooth flux density	K_{tr}	1.6 wb/m^2
Rotor core flux density	K_{cr}	1.6 wb/m^2
Air-gap flux density	B_g	1.65 wb/m^2 from the table (A-1)
Fixed input parameter of the designed generator	symbol	Value
Minimum stator slot pitch	τ_{ssmin}	7.5 mm
Maximum stator slot pitch	τ_{ssmax}	15 mm
Number of slots / pole / phase	q_s	3
Permeability of copper and aluminum	$\mu_\circ$	$4\pi * 10^{-7}$ H/m
Copper resistivity	ρ_{cuo}	$1.7 * 10^{-8}\ (\Omega.m)$
Aluminum resistivity	ρ_{alo}	$2.8 * 10^{-8}\ (\Omega.m)$
Thermal temperature coefficient of copper	$\propto_{cu}$	1/259
Thermal temperature coefficient of aluminum	$\propto_{a\ell}$	1/250
The form factor of magnetic flux	Φ_{ff}	0.75
Temperature conductivity factor	$\propto_{cond}$	833
Temperature convection factor	$\propto_{conv}$	50
Iron material density	γ_{id}	7800 k$_g$/m^3
Specific iron loss	$P_{i\ell s}$	2.5 watt/ k$_g$
Stator slot mouth width	bos	3 mm
Stator slot mouth height	hos	2 mm
Rotor slot mouth width	bor	3 mm
Rotor slot mouth height	hor	1 mm
Stator slot height between slot mouth height and slot first width.	hw	3 mm

2- The calculated input specifications data with their calculation formula as shown in table (2).

Table- 2: calculated input specifications data

The calculated input parameter	symbol	Calculation formula
Machine rated slip	s_r	$s_r = (N_s - N_r)/N_s$
Machine synchronous speed	n_s	$n_s = 2 * f_s/(2P)$ $(r.p.s)$
Stator angular frequency	w_s	$w_s = 2 * \pi * f_s$ rad./sec.
line-to-line voltage	$V_{\ell\ell}$	$V_{\ell\ell} = \sqrt{3} * V_{ph}$ (Volts)
Induced e.m.f coefficient	K_e	$K_e = 0.98 - 0.005 * P$

3- The variable input parameters as shown in table (3). These parameters can be changed in values by the computer program to obtain the optimal design.

Table- 3: variable input specifications data

Variable input parameters	symbol	Value
Volume controlling ratio = $\frac{stator\ stacklength}{pole\ pitch}$	λ_{vc}	1.1 from the table (A-2)
Inner to outer stator core diameter ratio	K_{ds}	0.62 from the table (A-3)
Stator conductor current density	J_{co}	$4 * 10^6$ A/m^2 from the table (A-4)
Rotor bar current density	J_b	$4 * 10^6$ A/m^2
Rotor end-ring current density	J_{er}	$5 * 10^6$ A/m^2
Specific electrical loading	A_c	25000 (A/m)
Specific stator slot loading	A_{ss}	500 (A. conductor)

4- Calculation of stator core dimensions as shown in table (4). This table shows the related parameters to the stator core dimensions and their related calculated formulas.

Table- 4: stator core dimensions and their related formulas

Parameter	symbol	Related formula
Apparent generator power	S_g	$S_g = P_{out}/(\eta * cos\phi)$ (VA)
Generator volume utilization factor or output coefficient	C_o	$C_o = K_{ff} * \phi_{ff} * K_{ws} * \pi * B_g * A_c$ ….. Joule/m^3
Stator bore diameter	D_{bs}	$D_{bs} = [2P * S_g/(Co * \pi * \lambda_{vc} * n_s)]^{\frac{1}{3}}$ ……. (mm)
Stator outer diameter	D_{os}	$D_{os} = D_{bs}/K_{ds}$ (mm)
Stator stack length	ℓ_{ss}	$\ell_{ss} = (\pi * \lambda_{vc} * D_{bs})/2P$ (mm)
Stator pole-pitch	τ_p	$\tau_p = (\pi * D_{bs})/2P$ (mm)
Maximum stator slot number	Q_{smax}	$Q_{smax} = \pi * D_{bs}/\tau_{ssmin}$ (mm)
Minimum stator slot number	Q_{smin}	$Q_{smin} = \pi * D_{bs}/\tau_{ssmax}$ (mm)
The suitable number of stator slots	Q_s	From table (A-5)
Stator slot pitch	τ_{ss}	$\tau_{ss} = \pi * D_{bs}/Q_s$ (mm)
Effective air-gap length	g_e	$g_e = 0.2 + 2 * [D_{bs} * \ell_{ss} * 10^{-6}]^{\frac{1}{2}}$ (mm)

5- Stator winding calculation, as shown in table (5).

This table shows the parameters related to the stator winding and their calculated formulas.

Table- 5: stator winding calculations

Parameters	Symbol	Related formula
Stator flux per pole	Φ_p	$\Phi_p = \phi_{ff} * \tau_p * \ell_{ss} * B_g$ (weber)
Stator turns per phase	N_{ph}	$N_{ph} = V_{ph}/(4 * K_e * K_{ff} * F_s * \Phi_p)$
Stator conductors per slot	S_{sc}	$S_{sc} = 2 * m * a_p * N_{ph}/Q_s$
Stator load line current	$I_{\ell\ell}$	$I_{\ell\ell} = P_{out}/(\eta * \sqrt{3} * V_{\ell\ell} * cos\phi)$ (A)
Stator load phase current	$I_{ph\ell}$	$I_{ph\ell} = I_{\ell\ell}$ (A)
Generator reactive power	Q_{gr}	$Q_{gr} = S_g * \sin(\phi)$ (VAR)
Stator self-excitation capacitive reactance	X_{cph}	$X_{cph} = 3 * V_{ph}^2/Q_{gr}$ (Ω)
Stator excitation current	I_{cph}	$I_{cph} = V_{ph}/X_{cph}$ (A)
Stator phase current	I_{sph}	$I_{sph} = [I_{ph\ell}^2 + I_{cph}^2]^{\frac{1}{2}}$ (A)
Stator specific slot loading	A_{ss}	$A_{ss} = S_{sc} * I_{sph}$ …. (A.cond.)
Stator winding conductor cross-sectional area	A_{co}	$A_{co} = I_{sph}/J_{co}$ (mm^2)
Stator winding conductor diameter	D_{co}	$D_{co} = 4 * A_{co}/\pi$ (mm)

6- Stator slot sizing calculations as shown in table (6). This table shows the related parameters to the stator slots and their formulas of calculation. The stator slot structure is shown in figure (2).

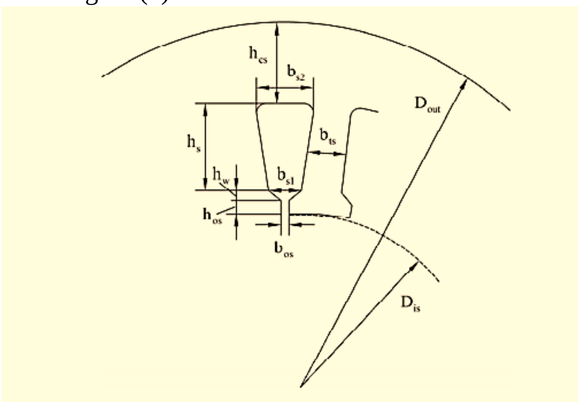

Fig. 2. Stator slot structure

Table- 6: Stator slot sizing calculations

Parameter	Symbol	Related calculation formula
Stator useful slot area	A_{use}	$A_{use} = A_{co} * S_{sc}/K_{fil}$ (mm^2) K_{fil} can be obtained from the table (A-6)
Stator tooth width	b_{ts}	$b_{ts} = B_g * \tau_{ss}/(K_{ts} * K_{fe})$ (mm)

Retrieval Number: 100.1/ijeat.A31981011121
DOI: 10.35940/ijeat.A3198.1011121
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Stator slot width (1)	b_{s1}	$b_{s1} = [\pi * (D_{bs} + 2 * h_{os} + 2 * h_w)/Q_s] - b_{ts}$ …….. (mm)
Stator slot width (2)	b_{s2}	$b_{s2} = [4 * A_{use} * tan(\pi/Q_s + b_{s1}^2)]^{\frac{1}{2}}$ (mm)
Stator useful slot height	h_{ss}	$h_{ss} = 2 * A_{use}/b_{s1} + b_{s2}$ (mm)
Stator back iron core height	h_{cs}	$h_{cs} = [D_{oc} - \{D_{bs} + 2 * (h_{os} + h_w + h_{ss})\}]/2$ ……………… (mm)

7- Calculation of rotor slots, bars, and end-ring sizing as shown in table (7).

This table shows the related formulas for the calculation of rotor slots, bars, and end-ring sizing. The rotor slot geometry is shown in figure (3).

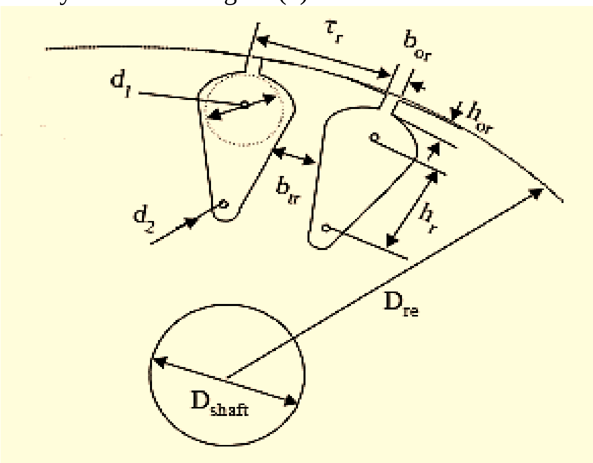

Fig. 3. Rotor slot structure

Table- 7: Rotor slots, bars, and end-ring sizing

Parameter	Symbol	Related calculation formula
Number of rotor slots	Q_r	From table (A-5)
Rotor current per phase referred to stator	$\acute{I}_{rph}$	$\acute{I}_{rph} = I_{sph}/K_{mm}$ (mm)
Rotor bar current	I_b	$I_b = 2 * m * N_{ph} * K_{ws} * \acute{I}_{rph}/Q_r$ (A)
Rotor slot area or rotor bar area	A_b	$A_b = I_b/J_b$ (mm^2)
Rotor end-ring current	I_{er}	$I_{er} = I_b/\left(2 * sin(\pi * P/Q_r)\right)$ (A)
Rotor end-ring cross-sectional area	A_{er}	$A_{er} = I_{er}/J_{er}$ (mm^2)
Rotor outer diameter	D_{or}	$D_{or} = (D_{bs} - 2 * g_e)$ (mm)
Rotor slot pitch	τ_{sr}	$\tau_{sr} = \pi *= (D_{bs} - 2 * g_e)/Q_r$ (mm)
Rotor tooth width	b_{tr}	$b_{tr} = B_g * \tau_{sr}/\left(K_{fe} * K_{tr}\right)$ (mm)
Rotor slot width	b_{sr}	$b_{sr} = (\tau_{sr} - b_{tr})$ (mm)
Rotor core height (core back iron)	h_{cr}	$h_{cr} = \Phi_p/(2 * \ell_{ss} * K_{cr})$ (mm)
Upper diameter of rotor slot geometry	d_1	$d_1 = \left[\pi * (D_{or} - 2 * h_{or}) - Q_r * b_{tr}\right]/(\pi + Q_r)$ (mm)
Lower diameter of rotor slot geometry(d_2 must be less than d_1)	d_2	$d_2 = \left[\left\{\left(32 * A_b * \tan(\pi/Q_r) - \left(8 + 4 * \pi * \tan(\pi/Q_r)\right) * d_1^2\right)\right\}/\left(4 * \pi * \tan(\pi/Q_r) - 8\right)\right.$ ……(mm)
Rotor slot depth	h_{sr}	$h_{sr} = (d_1 - d_2)/2 * \tan(\pi/Q_r)$ (mm)
Rotor end-ring height (radial thickness)	b	$b = 1.1 * (h_{sr} + h_{or} + (d_1 + d_2)/2)$ (mm)
Rotor end-ring width (axial thickness)	a	$a = A_{er}/b$ (mm)
Rotor shaft diameter	D_{sh}	$D_{sh} = \left[D_{or} - 2 * (h_{or} + \frac{(d_1+d_2)}{2} + h_{sr} + h_{cr})\right]$ (mm)

8- Calculation of stator resistance per phase as shown in table (8). This table shows all the parameters related to the calculation of stator resistance and their formulas.

Table- 8: calculation of stator resistance

Parameter	Symbol	Related calculation formula
Number of stator slots per pole	P_s	$P_s = Q_s/(2P)$
Chording factor	K_{ch}	$K_{ch} = cos\left(\pi/(2 * P_s)\right)$
Coil span	y_{sc}	$y_{sc} = \tau_p * K_{ch}$ (mm)
Length of end-turn from the table (A-7)	ℓ_{et}	$\ell_{et} = (y_{sc} + 20 * 10^{-3})$ (mm)
Length of one turn	ℓ_t	$\ell_t = 2 * (\ell_{ss} + \ell_{et})$ (mm)
Stator resistance per phase	R_s	$R_s = \rho_{cuo} * \ell_t * N_{ph}/(A_{co} * a_p)$ (Ω)

9- Calculation of rotor resistance per phase referred to stator side as shown in table (9). This table shows all the parameters related to the calculation of rotor phase resistance and their formulas.

Table- 9: calculation of rotor phase resistance

Parameter	Symbol	Related calculation formula
Length of end-ring per rotor slot	ℓ_{ers}	$\ell_{ers} = \pi * (D_{or} - 2 * h_{sr} - b)/Q_r$ (mm)
Skin effect factor	K_r	$K_r = h_{sr} * [2 * \pi * f_r * \mu_o/(2 * \rho_{alo})]^{\frac{1}{2}}$ Where $f_r = S.f_s$ rotor voltage frequency
Skew effect factor	K_{sq}	$K_{sq} = \sin(\pi * P/Q_r)/(\pi * P/Q_r)$
Rotor resistance per phase	R_r	$R_r = \left[\{\rho_{cuo} * \ell_{ss} * K_r/A_b\} + \{\rho_{alo} * \ell_{ers}/\left(2 * A_{er} * sin^2(\pi P/Q_r)\right)\}\right]$
Rotor resistance per phase referred to the stator side	$\acute{R}_r$	$\acute{R}_r = \left[4 * m * \left(N_{ph} * K_{ws}\right)^2/(Q_r * K_{sq}^2)\right] * R_r$

10- Calculation of stator leakage reactance per phase as shown in table (10).

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

This table shows the parameters calculation steps with their formulas, which are used to calculate the stator leakage reactance.

Table- 10: calculation of stator leakage reactance

Parameter	Symbol	Related calculation formula
Stator slot permeance	λ_s	$\lambda_s = \left[\left(2 * h_{ss} / \left(\left(3 * b_{s1} + b_{s2}\right)\right)\right) + \left(2 * h_w / (b_{s1} + b_{os})\right) + \left(h_{os}/b_{os}\right)\right] * (1 + 3 * K_{ch})/4$
Differential permeance of stator slot	λ_{ds}	$\lambda_{ds} = \left[(0.9 * \tau_{ss} * q_s^2 * K_{ws}^2 * C_s * \gamma_{ds}) / \left(K_{ca} * g_e * (1 + K_{st})\right)\right]$ Where $C_s = [1 - (0.033 * b_{os}^2/(g_e * \tau_{ss}))]$ γ_{ds} is a factor that can be obtained from the table (A-8). The parameter (θ) in the equation of (γ_{ds}) can be calculated as : $\theta = \pi * (6 * K_{ch} - 5.5)$
Stator end-turn permeance	λ_{et}	$\lambda_{et} = 0.34 * q_s * \left(\ell_{et} - 0.64 * K_{ch} * \tau_p\right) / \ell_{ss}$
Stator leakage reactance per phase	$X_{\ell s}$	$X_{\ell s} = \left[2 * \mu_o * \ell_{ss} * w_s * N_{ph}^2 * (\lambda_s + \lambda_{ds} + \lambda_{et}) / (P * q_s)\right]$ (Ω)

11- Calculation of rotor leakage reactance per phase as shown in table (11). The table involves all the parameters related to the rotor leakage reactance calculation with their formulas.

Table- 11: calculation of rotor leakage reactance

Parameters	Symbol	Relate formula of calculation
Rotor slot permeance	λ_r	$\lambda_r = [0.66 + (2 * hsr/(3 * (d_1 + d_2))) + h_{or}/b_{or}]$
Rotor slot differential permeance	λ_{dr}	$\lambda_{dr} = 0.9 * \tau_{sr} * \gamma_{dr} * Q_r^2/(K_{ca} * g_e(6 * P)^2)$ Where $\gamma_{dr} = 9 * (6 * P/Q_r)^2 * 10^{-2}$ K_{ca} = can be obtained from the table (A-9).
Rotor end-ring permeance	λ_{er}	$\lambda_{er} = \left[2.3 * (D_{or} - b)\left(Q_r * \ell_{ss} * 4 * sin^2(\pi * P/Q_r)\right)\right] * Log\,[4.7 * (D_{or} - b)/(b + 2\,.\,a)]$
Skin-effect factor	K_x	$K_x = 3/\left[2 * h_{sr} * \{w_s * \mu_o/(2 * \rho_{a\ell o})\}^{\frac{1}{2}}\right] * 10^{-3}$
Rotor leakage reactance per phase	$X_{\ell r}$	$X_{\ell r} = w_s * \mu_o * \ell_{ss} * (\lambda_r * K_x + \lambda_{dr} + \lambda_{er})$ (Ω)
Rotor leakage reactance per phase referred to the stator side	$\acute{X}_{\ell r}$	$\acute{X}_{\ell r} = \left[4 * m * \left(N_{ph} * K_{ws}\right)^2/(Q_r * K_{sq}^2)\right] * X_{\ell r}$ (Ω)

12- Calculation of magnetizing reactance per phase and the corrected rotor leakage reactance due to the skew effect as shown in table (12).

Table- 12: calculation of magnetizing reactance and the corrected rotor leakage reactance

Parameters	Symbol	Related calculation formula
Magnetizing reactance per phase	X_m	$X_m = w_s * K_{st} * \mu_o * m * \tau_p * \ell_{ss} * \left(N_{ph} * K_{ws}\right)^2/(\pi * P * g_e)$ (Ω)
Rotor leakage reactance due to skew-effect	$\acute{X}_{\ell rsq}$	$\acute{X}_{\ell rsq} = X_m * \left(1 - K_{sq}^2\right)$ (Ω)
Total rotor leakage reactance per phase	$\acute{X}_{\ell rt}$	$\acute{X}_{\ell rt} = \left(\acute{X}_{\ell r} + \acute{X}_{\ell rsq}\right)$ (Ω)

13- Calculation of magnetizing voltage and no-load current per phase as shown in table (13).

Table- 13: calculation of magnetizing voltage and no-load current

Parameters	Symbol	Related calculation formula
Magnetizing or air-gap phase voltage	V_g	$V_g = V_{ph} + I_{sph} * [R_s^2 + X_{\ell s}^2]^{\frac{1}{2}}$ (V)
No-load current / phase	I_o	$I_o = \left[\acute{I}_r^2 - I_{sph}^2\right]^{\frac{1}{2}}$ (A)
Rotor phase current	$\acute{I}_{rph}$	$\acute{I}_{rph} = V_g/\acute{Z}_r$ (A)
Magnetizing current per phase	I_m	$I_m = V_g/X_m$ (A)

14- Calculation of maximum and minimum excitation capacitance of the generator as shown in table (14). The maximum and minimum capacitance per phase can be calculated from the equivalent circuit of the generator.

Table- 14: maximum and minimum excitation capacitance per phase

Parameters	Symbol	Related calculation formula
Stator load loss resistance [5]	$R_{s\ell\ell}$	$R_{s\ell\ell} = R_s * X_{\ell s}^2/[R_s^2 + X_{\ell s}^2]$ (Ω)
Slip at maximum torque	S_{max}	$S_{max} = \acute{R}_r/\left[(R_s + R_{s\ell\ell})^2 + \left(X_{\ell s} + \acute{X}_{\ell r}\right)^2\right]^{\frac{1}{2}}$
Minimum rotor speed	W_{rmin}	$W_{rmin} = w_s * (1 - S_{max})$ $\frac{ele.rad}{sec.}$
Maximum rotor speed	W_{rmax}	$W_{rmax} = w_s * (1 + S_{max})$ $\frac{ele.rad}{sec.}$
Maximum excitation capacitance per phase	C_{emax}	$C_{emax} = 1/(W_{rmin}^2 * (X_m + X_{\ell s})\,/w_s)$ (μF)
Minimum excitation capacitance per phase	C_{emin}	$C_{emin} = 1/(W_{rmax}^2 * (X_m + X_{\ell s})\,/w_s)$ (μF)

15- Calculation of generator losses as shown in table (15).In this table, the details of losses calculation with their formulas are presented and then added to determine the total machine losses.

Table- 15: Generator losses calculation

Parameters	Symbol	Related calculation formula
Stator copper loss	P_{cus}	$P_{cus} = 3 * I_{sph}^2 * R_s$ (watt)
Rotor copper loss	P_{cur}	$P_{cur} = 3 * \acute{I}_r^2 * \acute{R}_r$ (watt)
Mechanical loss	P_{mec}	$P_{mec} = 0.012 * P_{out}$ from the table (A-10) (watt)
Iron core losses	P_{ic}	$P_{ic} = 3 * V_g * I_{ic}$ (watt) Where $I_{ic} = I_o * cos\phi_o$ (A)
Stray load losses	$P_{s\ell\ell}$	$P_{s\ell\ell} = 3 * I_{sph}^2 * R_{s\ell\ell}$ (watt)
Total machine losses	$P_{t\ell}$	$P_{t\ell} = P_{cus} + P_{cur} + P_{mec} + P_{ic} + P_{s\ell\ell}$

16- Calculation of generator temperature rise as shown in table (16).The table shows the stator and rotor winding resistivity calculation in terms of winding temperature rise.

Retrieval Number: 100.1/ijeat.A31981011121
DOI: 10.35940/ijeat.A3198.1011121
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Table- 16: temperature rise calculation of the stator winding

Parameters	Symbol	Related calculation formula
Machine frame area	A_{frame}	$A_{frame} = \pi * D_{os} * (\ell_{ss} + \tau_p) * K_{fins} * 10^{-6}$ (m^2)
Frame temperature	T_{frame}	$T_{frame} = P_{t\ell}/(\propto_{conv} * A_{frame})$ (℃) where $\propto_{conv}$ = 50 from table (A-11)
Stator winding temperature	$T_{winding}$	$T_{winding} = T_{ambient} + T_{frame}$ (℃) $T_{ambient} = 25$℃
The resistivity of the stator winding	ρ_{cu}	$\rho_{cu} = (1 + \propto_{cu} * T_{winding}) * \rho_{cuo}$ ($\Omega.m$)
The resistivity of rotor bars	$\rho_{a\ell}$	$\rho_{a\ell} = (1 + \propto_{a\ell} * (T_{winding} + 10)) * \rho_{a\ell o}$ ($\Omega.m$)

17- Calculation of optimized parameters of the generator as shown in table (17).The main parameters that are optimized in this design of the induction generator are efficiency, excitation-capacitance, stator winding temperature, and the generator volume.

Table- 17: optimized parameters calculation

parameters	Symbol	Related calculation formula
Generator efficiency	$\eta\%$	$\eta\% = [P_{out}/(P_{out} + P_{t\ell})] * 100$
Excitation capacitance	C_{emin}	$C_{emin} = 1/[w_{rmax}^2 * (X_m + X_{\ell s})/W_s]$
Stator winding temperature	$T_{winding}$	$T_{winding} = T_{ambient} + T_{frame}$
Generator volume	$Volume$	$Volume = (\pi * D_{os}^2 * \ell_{ss}/4) * 10^{-3}$ (C_m^3)

III ANT COLONY OPTIMIZATION

In this paper, for example, a 5-HP squirrel-cage, self-excited induction generator, 50 Hz and 400 V line-to-line is designed and optimized. The objective function is used for maximum efficiency, minimum excitation capacitance, minimum generator volume, and minimum temperature rise. The ant colony algorithm parameters are given as [12] :

$$F_{(x,w)} = W_1 * \frac{1}{[1+\eta]} + W_2 * C_{emin} + W_3 * volume + W_4 * T_{winding}$$

Where W_1, W_2, W_3 and W_4 are the weights that indicate the relative significance among the chosen objectives. These weight parameters can be set to one for activating the objective function. The multi-objective optimization problem can be suited by combining many objectives through weight parameters into a single objective to optimize the chosen objectives (involves both minimizations and maximization) simultaneously.

IV RESULTS AND DISCUSSION

The ant colony optimization algorithm is used to obtain the optimal design parameters of the squirrel-cage, self-excited induction generator.The design equations in tables (2-17) are used to feed the computer program in a sequence and systematic arrangement of the design procedure. The software package is developed and executed in a Matlab file. The final machine design results are obtained by optimizing the objectives of efficiency, excitation capacitance, machine volume, and stator winding temperature rise. It is clear from tables (18-19), which are the results of the design, those better design parameters are obtained when the weights $W_1 = W_2 = W_3 = W_4 = 1$ in the ant colony algorithm of optimization. Table (18) shows the results of all machine construction parameters, while table (19) shows the optimal results of objective parameters. The algorithm offers maximum machine efficiency and minimum excitation capacitance, minimum size, and minimum stator winding temperature rise. In this case study, the machine efficiency is 88%, the minimum excitation capacitance per phase is 25μF , the minimum volume of the machine is 2260 C_m^3 and the minimum stator winding temperature rise is 50 ℃.

Table- 18: Design specifications of the generator construction parameters

Generator construction parameters	Symbol	Dimension
Stator stack length/pole pitch	λ_{vc}	1.15
Inner to outer stator core diameter	K_{ds}	0.625
Stator conductor current density	J_{co}	$4.5 * 10^6$ A/m^2
Rotor bar current density	J_b	$4.5 * 10^6$ A/m^2
Rotor end-ring current density	J_{er}	$5.5 * 10^6$ A/m^2
Specific electrical loading	A_c	23500 A/m
Specific stator slot loading	A_{ss}	450 A. conductor
Apparent generator power	S_g	4725 VA
Generator volume utilization factor	C_o	35900 Joule / m^3
Stator outer diameter	D_{os}	57 mm
Stator stack length	ℓ_{ss}	195 mm
Stator pole-pitch	τ_p	44.5 mm
Stator slot number	Q_s	24
Effective air-gap length	g_e	1.12 mm
Stator flux per pole	ϕ_p	0.013 weber
Stator turns per phase	N_{ph}	165
Stator phase current	I_{sph}	7.0 A
Stator winding conductor area	A_{co}	1.5 mm^2
Stator winding conductor diameter	D_{co}	1.4 mm
Stator useful slot area	A_{use}	21.0 mm^2
Stator tooth width	b_{ts}	3.0 mm
Stator slot width (1)	b_{s1}	4.5 mm
Stator slot width (2)	b_2	2.5 mm
Stator useful slot height	h_{ss}	15.0 mm
Stator back-iron core height	h_{cs}	16.0 mm
Rotor slot number	Q_r	22
Rotor phase current	$\acute{I}_{rph}$	7.3 A
Rotor bar current	I_b	164 A
Rotor slot area	A_b	36.5 mm^2
Rotor end-ring current	I_{er}	264 A
Rotor end-ring cross-sectional area	A_{er}	48 mm^2
Rotor outer diameter	D_{or}	54.5 mm
Rotor slot pitch	τ_{sr}	7.9 mm
Rotor tooth width	b_{tr}	3.0 mm
Rotor slot width	b_{sr}	4.9 mm
Rotor core height	h_{cr}	11.0 mm
Rotor upper slot diameter	d_1	4.6 mm
Rotor lower slot diameter	d_2	1.0
Rotor slot depth	h_{sr}	7.5 mm
Rotor end-ring height	b	8.0 mm
Rotor end-ring width	a	6.5 mm
Rotor shaft diameter	D_{sh}	33.1 mm
Stator resistance per phase	R_s	3.1 Ω
Rotor resistance per phase	$\acute{R}_r$	2.5 Ω
Stator leakage reactance per phase	$X_{\ell s}$	1.8 Ω
Rotor leakage reactance per phase	$\acute{X}_{\ell r}$	0.85 Ω
Magnetizing reactance per phase	X_m	140 Ω
Magnetizing or air-gap voltage / phase	V_g	250 Ω
No-load current per phase	I_o	2.0 A
Magnetizing current per phase	I_m	1.8 A
Iron core current per phase	I_{ic}	0.9 A
Iron core resistance per phase	R_{ic}	280 Ω

Retrieval Number: 100.1/ijeat.A31981011121
DOI: 10.35940/ijeat.A3198.1011121
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Table- 19: objective design parameters of the generator

Parameters	Symbol	Dimension
Minimum excitation capacitance per phase	C_{emin}	25 μF
Stator winding temperature	$T_{winding}$	52 ℃
Generator volume	$Volume$	2270 C_m^3
Generator efficiency	$Efficiency$	88 %

V CONCLUSION

Design steps with their suitable theoretical and empirical formulas are executed in the computer program and Matlab file to obtain the structure dimensions and parameters of the 3-phase squirrel-cage self-excited induction generator. The design steps are summarized in sequence tables and systematic manner. The new design dimensions and parameters of the generator suit the generator operation in the stable and saturation region. The design results are optimized by an ant colony optimization algorithm. The objective parameters are used in this algorithm to obtain maximum generator efficiency and minimum excitation capacitance, minimum winding temperature rise, and minimum generator size. A generator of 5 HP, 400 V, 50 Hz, and Y-connection is used as an example of the design procedure.

APPENDIX [14]

Table- A-1: Air-gap flux density as a function of number of magnetic poles

Poles Number (2P)	2	4	6	8
Air-gap density (wb/m^2)	0.5-0.75	0.65-0.78	0.7-0.82	0.75-0.85

Table- A-2: Volume control parameter (λ_{vc}) as a function of the number of poles

Poles Number (2P)	2	4	6	8
Volume controlling ratio (λ_{vc})	0.6-1.0	1.2-1.8	1.6-2.2	2-8

Table- A-3: Stator inner to outer diameter ratio (K_{ds}) as a function of poles number

Poles Number (2P)	2	4	6	8
Ratio (K_{ds})	0.54-0.58	0.61-0.68	0.68-0.71	0.72-0.74

Table- A-4: current density of stator winding as a function of poles number

Poles Number (2P)	2 or 4	6 or 8
A current density of stator winding (J_{co})	4-7 A/mm^2	5-8 A/mm^2

Table- A-5: stator and rotor slot number as a function of poles number

(2P)	Q_s	24	36	48	—
2	Q_r	18 20	32 30 28	44 40 30	
4	Q_s	24	36	48	72
	Q_r	22 18	34 30 28	46 42 36	70 66 62
6	Q_s	—	36	54	72
	Q_r		32 28 22	46 44 40	68 64 62
8	Q_s	—	—	48	72
	Q_r			38 36	60 56

Table (A-6) stator slot filling factor (K_{fil})

$K_{fil} = 0.35 \longrightarrow 0.4$	For machines less than 10 kw
$K_{fil} = 0.4 \longrightarrow 0.44$	For machines above 10 kw

Table- A-7: end-ring length as a function of poles number and coil span (y_{sc})

Poles number (2P)	End turn (ℓ_{et}) as a function of coil span	
2	$\ell_{et} = (2 * y_{sc} - 0.04), y_{sc}$	in meter
4	$\ell_{et} = (2 * y_{sc} - 0.02), y_{sc}$	in meter
6	$\ell_{et} = (\frac{\pi}{2} * y_{sc} + 0.018), y_{sc}$	in meter
8	$let = (2.2 * y_{sc} - 0.012), y_{sc}$	in meter

Table- A-8: The factor (γ_{ds}) as a function of number of slots / pole / phase (q_s)

q_s	The factor γ_{ds} in the equation of stator slot differential permeance
1	$\gamma_{ds} = 9.5 * 10^{-2}$
2	$\gamma_{ds} = (0.25 * \sin(\theta) + 2.6) * 10^{-2}$
3	$\gamma_{ds} = (0.18 * sin(\theta) + 1.24) * 10^{-2}$
4	$\gamma_{ds} = (0.24 * \sin(\theta) + 0.76) * 10^{-2}$
6	$\gamma_{ds} = (0.11 * sin(\theta) + 0.41) * 10^{-2}$

Table- A-9: Carter coefficient (K_{ca})

$K_{ca} = 1.2 - 1.3$	For semi-closed stator slots
$K_{ca} = 1.5 - 1.7$	For open-stator slots

Table- A-10: Machine mechanical losses (P_{mec}) as a function of pole-pairs

pole-pairs (P)	Mechanical losses (P_{mec}) in terms of P_{out}
1	$P_{mec} = 0.03 * P_{out}$
2	$P_{mec} = 0.012 * P_{out}$
3, 4	$P_{mec} = 0.008 * P_{out}$

Table- A-11: temperature convection coefficient ($\propto_{conv}$) as a function of poles number

Poles number (2P)	$\propto_{conv}$ (W/m^2. K)
2	60
4	50
6	40
8	32

REFERENCES

1. A.K. Al-Jabri and A.I. Alolah," Limits on the performance of the three-phase self-excited induction generators ", IEEE Transactions on Energy Conversion, Vol. 5, No. 2, Pp 350-356, June 1990.
2. B. Sawetsakulanond, P. Hothongkham, and V. Kinnares, " Investigation on the performance between standard and high-efficiency induction machines operating as grid-connected induction generator ", IEEE ICSET, Pp 949-953, 2008.
3. B. A. Nasir," Modeling of a self-excited induction generator in the synchronously rotating frame including dynamic saturation and iron core loss into account ", International Journal of Electrical and Computer Science, Vol. 20, No. 1, Pp 1-6, February 2020.
4. B. A. Nasir," and R.W. Daoud, " Modeling of wind turbine - self-excited induction generator system with pitch angle and excitation capacitance control ", AIP Conference Proceedings, Vol. 2307, No. 1, Pp 1-21, December 2020.
5. B. A. Nasir, " An accurate iron core loss model in the equivalent circuit of induction machines ", Journal Of Energy, Hindawi Publisher, Vol . 2020, Article ID 7613737, Pp 1-10, 2020.

6. J. Faiz, A. A. Dadgari, S. Horning and A. Keyhani, " Design of a three-phase self-excited induction generator ", IEEE Transactions on Energy Conversion, Vol. 10, No. 3 Pp 516-52, 1995.
7. B. Sawetsakulanond, P. Hothongkham, and V. Kinnares, " Design and construction of three-phase of self-excited induction generator ", IEEE ICSET, Pp 1373-1378, 2008.
8. Ion Boldea, " Wound-rotor induction generators: Design and testing: Variable speed generators ", Book, CRC Press, 6 October 2015.
9. B. Kareem, T. Ewetumo, M.K. Adeyeri, A. Oyetunji, and S.T. Olowookere, " Development of electricity generating system for a micro-power plant ", Journal of Production Engineering, Vol. 21, No. 2, Pp 43-49, 2018.
10. A.G. Yetgin, M. Turan, B. Cevher, A.I. Canakoglu, and A. Gun, " Induction motor design process and the effect of output coefficient ", 7th International Conference on Advanced Technologies (ICAT ' 18), Pp 152-159, April / May 2018.
11. P.S. Prakash, " Multi-objective design of induction motor using artificial intelligence techniques ", International Research Journal Of Engineering Technology (IRJET), Vol. 4, No. 7, Pp 3529-3535, July 2017.
12. P.S. Prakash, " Elegant design strategy for multi-objective optimization of induction motors ", International Research Journal of Engineering and Technology (IRJET), Vol. 4, No. 8, Pp 2395-2401, August 2017.
13. B. Alizadeh and S.A. Gholamian, " Application of Ant colony optimization algorithm for the optimal design of squirrel cage induction motor ", International Journal of Mechatronic, Electrical and Computer Technology, Vol. 4, No. 13, Pp 1674-1690, October 2014.
14. I. Boldea and S.A. Nasar, " The induction machines design handbook ", Second Edition, Taylor and Frances Group, CRC Press, 2010.

AUTHORS PROFILE

Bilal A. Nasir , (Non-member) He was born in 1958, Iraq. He received B.Sc. of electrical engineering from university of Technology, Baghdad-Iraq, 1980, and M.Sc. of electrical engineering from university of Mosul, Iraq, in 1984 and PH.D. of electrical engineering from Al-Mustansiriyah university, Iraq, in 1997. He has been employed as a lecturer in Northern Technical University ,Iraq /Hawijah Technical Institute, Kirkuk, Iraq from 1988 up to date. Now he was an assistant professor in electrical power and machines.

Retrieval Number: 100.1/ijeat.A31981011121
DOI: 10.35940/ijeat.A3198.1011121
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)