Modeling and Simulation of 1.1 kW Wind Energy Conversion System

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***Abstract*—Over the last thirty years, renewable energy sources have been attracting great attention due to the cost increase, limited reserves, and environmental impact of fossil fuels. In the main time, technological advancements, cost reduction, and governmental incentives have made some renewable energy sources more competitive in the market. Among them, wind energy is one of the fastest growing renewable energy sources. This work is applied to investigate whether WADI-SEIDNA region (North Khartoum, Sudan) is suitable to generate electrical power or not, according to a design and modeling of horizontal blade turbine. A detailed mathematical model of a squirrel-cage induction generator (SCIG) coupled to wind turbine system using vector control computing technique is also done. The performance of wind energy conversion system (WECS) is studied using simulation developed in MATLAB/SIMULINK.**

***Keywords*— WECS, SCIG, Horizontal blade data design, Vector control.**

I. INTRODUCTION

It is commonly accepted that the earth's fossil energy resources are limited, and the global oil, gas and coal production will come beyond their peak in the next decades, and price rises will continue. At the same time there is strong political opposition against strengthening nuclear power in many parts of the world. In this scenario renewable energies will have to contribute more and more to the world's ever rising need of energy in the future. Renewables are climate-friendly forms of energy, due to the absence of emissions detrimental to the environment. Utilization of renewables is mostly with conversion into electrical energy. While water power has been used in electrical power stations and pumped storage systems since many decades, the use of wind power conversion in larger ratings has begun only in the 1980s. Wind energy systems are about to reach the competitiveness before long, while photovoltaic energy production is still expensive and will require further support on their way to market relevance [1].

Wind are essentially caused by the solar heating of the atmosphere. They carry enormous quantity of energy. Before the development of electric power on large scale, wind power has served many countries as source of power in early days and were called as wind mills. Wind power has been used for centuries to sail vessels, pump water, and grind wheat and corn. Wind as a source of power is very attractive because it is plentiful, inexhaustible, renewable, and non-polluting. There is no depletion of scarce resources. In large portion of the world, wind blows for 320 days in a year and this gives them an advantage over sunlight in direct conversion programs operating cost of a wind mill is negligible. Further, it does not impose extra heat burden on environment [2]. The evolution of wind power conversion technology has led to the development of different types of wind turbine configurations that make use of a variety of electric generators. Depending on their construction and operating principle, the wind generators are divided in two main groups: induction generators (IGs) and synchronous generators (SGs). Both induction and synchronous generators have wound rotors, which are fed by slip rings through brushes or by a brushless electromagnetic exciter. The wound-rotor induction generator, also known as the doubly fed induction generator (DFIG), is one of the most commonly used generators in the wind energy industry [3]. The wound-rotor synchronous generator (WRSG) is also found in practical WECSs with high numbers of poles operating at low rotor speeds. Squirrel-cage induction generators (SCIGs) are also widely employed in wind energy systems where the rotor circuits (rotor bars) are shorted internally and therefore not brought out for connection with external circuits. In permanent-magnet synchronous generators (PMSGs), the rotor magnetic flux is generated by permanent magnets [4]. Two types of (PMSG) are used in the wind energy industry: surface mounted and inset magnets. (SCIGs) as a fixed system is most common used in (WECS) systems The configuration of Fixed speed (WECS) is simple, low costs for manufacturing, installation and maintenance and reliable operation compared to the variable speed (WECS) [5,6]. The blade is the most important component of the (WECS) systems, the generator shaft is driven by the turbine either horizontal axis wind turbines (HAWT) or vertical axis wind turbines (VAWT) and its stator is directly connected to the grid [7,8].

II. MATHEMATICAL MODEL OF SCIG

A. Space-Vector Model

The induction generator (IG) space-vector model is generally composed of three sets of equations: voltage equations, flux linkage equations, and motion equation [1, 7]. The voltage equations for the stator and rotor of the IG in the arbitrary reference frame are given by:

$$\begin{aligned}\vec{V}_s &= R_s\vec{i}_s + p\vec{\lambda}_s + j\omega\vec{\lambda}_s \\ \vec{V}_r &= R_r\vec{i}_r + P\vec{\lambda}_r + j(\omega-\omega_r)\vec{\lambda}_r\end{aligned} \quad (1)$$

Where, $\vec{V}_s, \vec{V}_r$, $\vec{i}_s, \vec{i}_r$, $\vec{\lambda}_s, \vec{\lambda}_r$, R_s, R_r, are the voltages, currents, flux linkage, and winding resistance vectors of the stator and rotor respectively. ω , and ω_r is the rotor speed and electrical angular speed (rad/sec) respectively, and p is the derivative operator. The second set of equations is for the stator and rotor flux linkages $\vec{\lambda}_r$ and $\vec{\lambda}_S$:

$$\vec{\lambda}_s = (L_{Is}+L_m)\vec{i}_s + L_m\vec{i}_r = L_s\vec{i}_s + L_m\vec{i}_r$$

$$\vec{\lambda}_r = (L_{Ir}+L_m)\vec{i}_r + L_m\vec{i}_s = L_r\vec{i}_r + L_m\vec{i}_s \quad (2)$$

Where, L_s, L_r, are the stator and rotor self-inductances (H), L_m is the magnetizing induction (H), and L_{is}, L_{ir} are stator and rotor leakage inductances (H) respectively. The motion equation is:

$$j\,\frac{dw_m}{dt} = T_e - T_m$$

$$T_e = \frac{3P}{2}\,\mathrm{Re}\left(j\vec{\lambda}_s\vec{i}_s^*\right) = -\frac{3p}{2}\,\mathrm{Re}\left(j\vec{\lambda}_r\vec{i}_r^*\right) \quad (3)$$

Where, j moment of inertia of the rotor (Kg/m^2), P is the number of pair poles, T_m is the mechanical torque from the generator shaft ($N.m$), T_e is the electromagnetic torque ($N.m$), and ω_m is the rotor mechanical speed (rad/sec). The dq axis model of the IG can be obtained by decomposing the space-vectors into their corresponding d and q axis components as follows:

$$\begin{aligned}&\vec{V}_s = v_{ds} + jv_{qs}\,;\ \vec{i}_s = i_{ds} + j\,i_{qs}\,;\ \vec{\lambda}_s = \lambda_{ds} + \lambda_{qs} \\ &\vec{V}_r = v_{dr} + jv_{qr}\,;\ \vec{i}_r = i_{dr} + j\,i_{qr}\,;\ \vec{\lambda}_r = \lambda_{dr} + \lambda_{qr}\end{aligned} \quad (4)$$

From equations (1) and (4), the dq axis voltage equations for the IG are obtained:

$$\begin{aligned}v_{ds} &= R_s\,i_{ds} + p\lambda_{ds} - \omega\lambda_{qs} \\ v_{qs} &= R_s\,i_{qs} + p\lambda_{qs} + \omega\lambda_{ds} \\ v_{dr} &= R_r\,i_{dr} + p\lambda_{dr} - (\omega-\omega_r)\lambda_{qr} \\ v_{qr} &= R_r\,i_{qr} + p\lambda_{qr} + (\omega-\omega_r)\,)\lambda_{dr}\end{aligned} \quad (5)$$

Similarly, from equations (2) and (4), the dq axis flux linkages are obtained:

$$\begin{aligned}\lambda_{ds} &= (L_{ls+}L_m)i_{ds} + l_m i_{dr} = L_s\,i_{ds} + L_m\,i_{dr} \\ \lambda_{qs} &= (L_{ls+}L_m)i_{qs} + l_m i_{qr} = L_s\,i_{qs} + L_m\,i_{qr} \\ \lambda_{dr} &= (L_{ls+}L_m)i_{dr} + l_m i_{ds} = L_s\,i_{dr} + L_m\,i_{ds} \\ \lambda_{qr} &= (L_{ls+}L_m)i_{qr} + l_m i_{qs} = L_s\,i_{qr} + L_m\,i_{qs}\end{aligned} \quad (6)$$

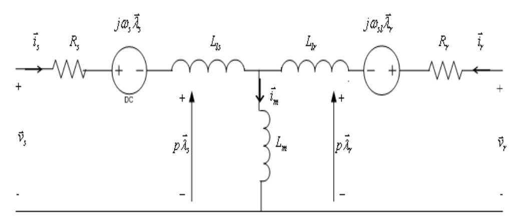

Fig. (1.a): IG model in the synchronous frame.

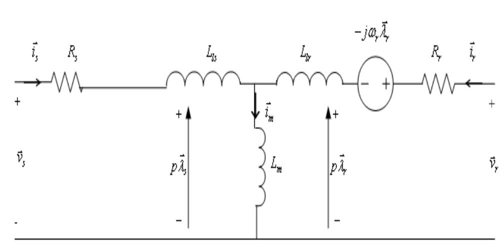

Fig. (1.b): IG model in the stationary frame.

Fig. 1: Space-vector models for IG in the synchronous and stationary reference frames.

The electromagnetic torque T_e in Equation (3) can be expressed by dq axis flux linkages and currents as well. By mathematical manipulations, several expressions for the torque can be obtained. The most commonly used expressions are given by:

$$T_e = \begin{cases} \frac{3P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) \\ \frac{3PL_m}{2}(i_{qs}i_{dr} - i_{ds}i_{qr}) \\ \frac{3PL_m}{2L_r}(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}) \end{cases} \quad (7)$$

B. Simulation Model

To build the simulation model, the equations derived previously should be rearranged. Equation (5) can be rewritten as:

$$\begin{aligned} \lambda_{ds} &= (v_{ds} + R_s i_{ds} + \omega\lambda_{qs})/s \\ \lambda_{qs} &= (v_{qs} + R_s i_{qs} + \omega\lambda_{ds})/s \\ \lambda_{dr} &= (v_{dr} + R_r i_{dr} + (\omega - \omega_r)\lambda_{qr})/s \\ \lambda_{qr} &= (v_{qr} + R_r i_{qr} + (\omega - \omega_r)\lambda_{dr})/s \end{aligned} \quad (8)$$

The flux linkage equations shown in equation (6) can be represented in a matrix form:

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \cdot \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (9)$$

The stator and rotor currents in the above equation can be expressed in terms of stator and rotor flux linkages.

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \frac{1}{D_1} \begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \cdot \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} \quad (10)$$

Where, $D_1 = L_S L_r - L_m^2$. The motion and torque equations for the simulation model are given by:

$$\begin{aligned} \omega_r &= \frac{P}{JS}(T_e - T_m) \\ T_e &= \frac{3P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) \end{aligned} \quad (11)$$

III. MODELIN AND SIMULATION OF 1.1KW WECS

A. Introduction

The complete wind energy conversion system composed of three main parts, turbine, gearbox and generator. The system composed of a model of an aerodynamics blade of the turbine, a drive train gear, and SCIG model.

B. Simulation block of Wind Turbine

According to the horizontal blade design parameters shown in Table 1 and Table 2 below, the complete simulation of 1.1 kW WECS can be achieved by using the aerodynamic equations representing the output power from the turbine due to the flow of wind stream, the wind turbine block has been assembled. The equations used in the simulation blocks are given in the actual output power equation as shown below:

$$P_{out} = \frac{1}{2}\rho A v^3 (\eta_{mech} C_p) \quad (12)$$

These blocks consist the following:

- Block for calculating lambda, λ.
- Block for calculating the power coefficient, C_p.
- Block for calculating the turbine torque, $T_{turbine}$.
- Block for calculating the mechanical power, P_m.

Table 1: Parameters of the blade design.

B	ρ	λ	R	Ω	R.P.M	C_l	α
3	1.22	7.9	1.96	12.7	1500	0.7523	6.25

Table 2: Final blade design.

r(m)	λ_r	ϕ	C	θ_p
0.196	0.79	47.66	0.383	41.14
0.392	1.58	28.76	0.305	22.51
0.588	2.37	20.09	0.23	13.84
0.784	3.16	15.34	0.182	9.09
0.98	3.95	12.38	0.148	6.13
1.176	4.74	10.37	0.127	4.12
1.372	5.53	8.91	0.109	2.66
1.568	6.32	7.81	0.095	1.56
1.764	7.11	6.95	0.0852	0.7
1.96	7.9	6.26	0.0769	0.01

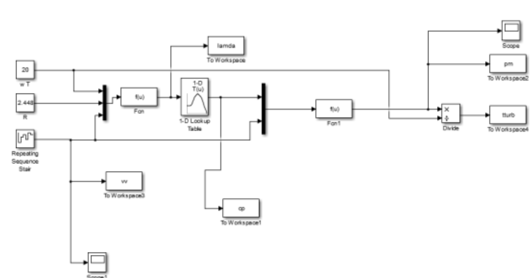

Fig.2: Modeling of the wind turbine.

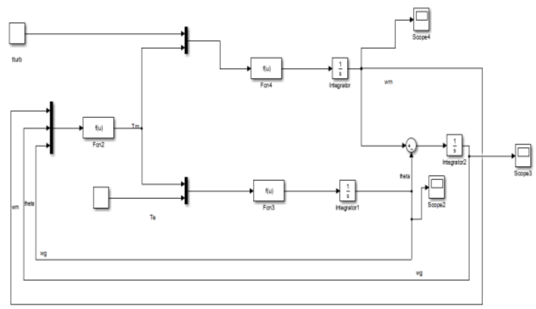

Fig.3: Modeling of the gearbox.

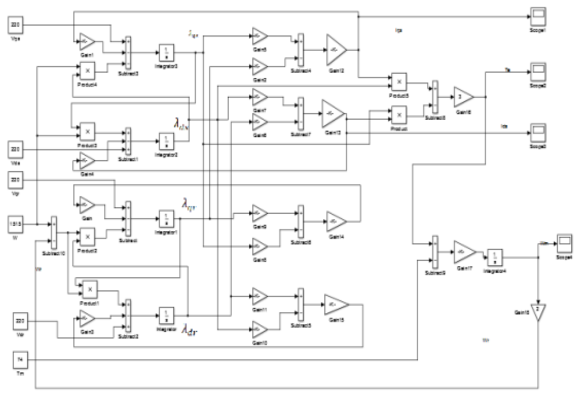

Fig.4: Modeling of the generator.

Figures 5 to 10 shows the simulation results of the SCIG, power, currents, torque, and mechanical speed.

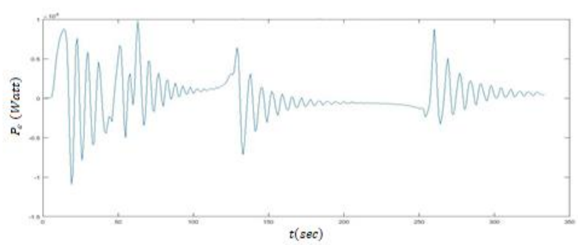

Fig.5: SCIG simulation of generator power.

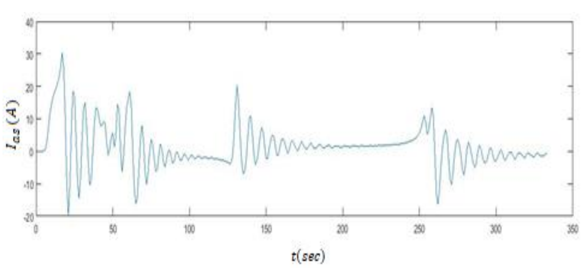

Fig.6: SCIG simulation of current phase a.

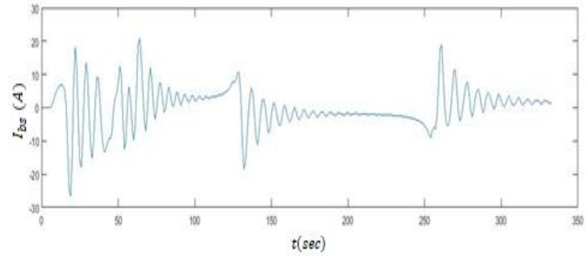

Fig.7: SCIG simulation of current phase b.

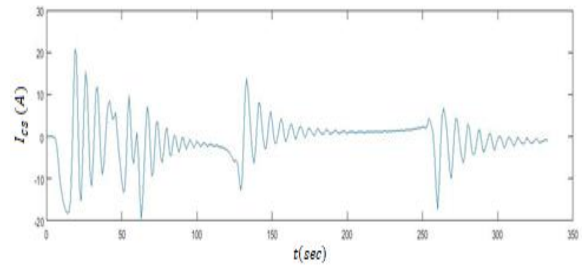

Fig.8: SCIG simulation of current phase c.

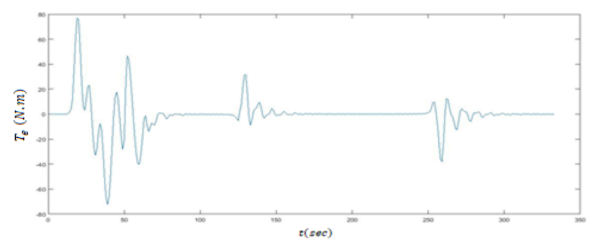

Fig.9: SCIG simulation of electrical torque.

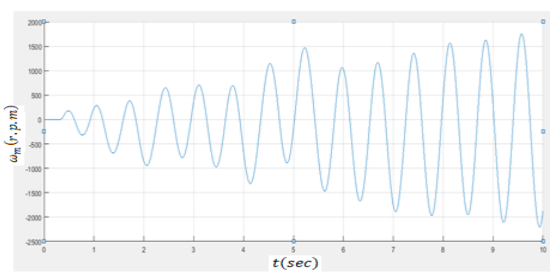

Fig.10: SCIG simulation of mechanical speed.

V. CONCLUSION

This work is applied to investigate whether WADI-SEIDNA region (North Khartoum, Sudan) is suitable to generate electrical power or not. According to the horizontal blade design parameters shown in Table 1 and Table 2 above, the complete simulation of 1.1 kW Wind Energy Conversion System (WECS) is presented. Then a detailed mathematical model of SCIG coupled to wind turbine system using vector control computing technique is achieved. The performance of (WECS) is also studied using simulation developed in MATLAB/SIMULINK. The Simulation is done by using the data of wind speed in WADI-SEIDNA region, with the aid of SCIG data sheet, and then through the MATLAB package. The simulation results are that, the electrical variable power is in the range of (0.85 to 5.5) kW, when the turbine started with a speed range of (3-4 m/sec), and according to the wind speed data sheet for WADI SEIDNA area, a generation station can be constructed to generate different amounts of the electric power by using the wind energy.

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APPENDIX

1.1kW SCIG, 220V, 50Hz, Parameters.

Generator type	SCIG,1.1 kW , 220V, 50Hz
Phase	3 Ø
Rated voltage	220 V
Rated current	2.425 A
Speed	1515 rpm
Stator resistance	7.83 Ω
Rotor resistance	7.55 Ω
Stator inductance	0.4535 H
Rotor inductance	0.475 H
Magnetizing of pole	0.3 H
Number of pole	4
Rotor inertia	0.664 kg.m^2