An Accurate Efficiency Calculation for PMSG Utilized in Renewable Energy Systems

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Abstract—**Considering the importance of optimizing renewable energy systems, this paper aims at calculating the exact efficiency of a stand-alone wind turbine connected to a synchronous generator with permanent magnet excitation (PMSG). By accounting for mechanical and electrical losses (copper losses, stray load losses, iron core losses, friction losses, windings losses, and magnetizing saturation effect), the study investigates the impact of wind speed on the generator's performance and efficiency in addition to the impact of losses on the overall efficiency of (PMSG). The simulation of the PMSG dynamic model $8.5 \times (10)^3$ V.A is executed using MATLAB/Simulink, employing a simplified equivalent circuit that accurately represents the PMSG's behavior under steady-state conditions with resistive loads. Wind speeds of 12 and 14 meters/second are chosen as fixed values to demonstrate the effect of varying wind speed on efficiency. The obtained results reveal the influence of wind speed on the PMSG efficiency. The presented findings contribute to the understanding of PMSG performance and can aid in optimizing the stand-alone wind turbine systems, they also show that the wind had an effect on the efficiency values that were obtained (97.86% at 12m/s and 97.91% at 14 m/s), while the effect of losses was very few around 3%. However, the obtained results are very good compared to previous studies to show the accuracy and validity of the suggested dynamic model.**

Keywords*—*PMSG; Synchronous Generator; Wind Speed Effect; Stand-Alone Wind Turbine; Efficiency Calculations.

I. INTRODUCTION

Research on electrical machines connected to wind energy conversion systems, such as permanent magnet synchronous generators (PMSGs), has gained significant importance in recent years due to the growing demand for renewable energy systems [1][2][3]. The wind turbine efficiency is 59.2% [4].

Previous studies by Anton Aleksashkin and Aki Mikkola, (2008) have explored the applications of permanent magnet machines in various industrial sectors, including their use in wind energy systems for electric power generation [5]. Bilal Abdullah Nasir (2020) has also focused on accurately calculating iron core losses in electrical machines, which account for a substantial portion of total losses and are influenced by variables such as supply voltage and core temperature [6]. Udhayakumar P, Saravanan C, and Lydia M (2013) focused on studying the output voltage performance of the PMSG directly connected to the wind turbine by using PWM (Pulse Width Modulation) under variable and fluctuating speed, where the simulation results were affected the voltages by the wind speed [7]. B. Abdullah Nasir and R. W. Daoud focused on analyzing and simulation the PMSG used in renewable energy systems to demonstrate the performance of PMSG, the simulation results showed validity and effectiveness compared to the experimental results [8].

In line with the increasing demand for renewable energy sources and the limitations of conventional energy options like coal and natural gas, there is a rising need for clean energy alternatives, including tidal, solar, and wind energy [9][10][11]. Among various types of generators, the PMSG stands out as a widely used solution, particularly in isolated substations within wind energy conversion systems (WECSs) with micro-capacity [12]. The PMSG offers numerous advantages including: due to the absence of excitation circuits as slip-rings, windings of the rotor, and Carbone brushes given its high reliability and lightweight design [13][14], the high density of power and simple control methods in dealing with good active and reactive power control with high precision [15][16][17], low losses due to self-excitation without rotor copper losses led to high efficiency and then, low maintenance [18][19], this kind of synchronous alternator is possible to work with a large number of magnetic pole pairs also no need for a gearbox [20][21]. It works widely in commercial and industrial applications as renewable energy, especially wind power conversion systems [22], Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV) [23][24], home appliances and elevators [25][26], it has a high torque generating capacity, but higher torque with ripple due to inductance low and saliency [27],the energy storage systems in a flywheel [28], high power factor comparing to DFIG, WRSG, SCIG etc. [29]–[31].

For the above advantages of PMSG that are used in renewable energy conversion, each of the researchers [32]-[43] who worked in this field had a relation to this topic in terms of analysis, representation, design, and control of this type of synchronous generator. But all those researchers did not include mechanical and electrical losses such as iron losses, stray load losses, friction losses, and magnetizing saturation effects in the mathematical calculations. In addition, there are no results in their analyses that indicate the validity of the mathematical paradigm. These kinds of machine losses cannot be neglected when efficiency and performance are required.

At least there are two research contributions. First, the main contribution to the science is that the idea of resonance phenomenon in electrical circuit can be used in the renewable energy systems to obtain very high efficiency, very low losses and very good performance in this type of system. Secondly, showing the effect of different fixed wind speeds (12 and 14 meters per second) on the efficiency of PMSG within matlap/Simulink environment. The fixed-wind speed turbines have many benefits, including high reliability, a simple electrical system, and moderate cost [44]. The equivalent machine circuits have been modified for comprehensive analysis without increasing the number of system differential equations in the course of maintaining the accuracy of the efficiency calculation by representing the iron core losses as iron core resistance**,** connected in parallel with magnetizing inductance and then reflected in the form of voltage drop in the stator circuit [8][45]. The load stray is represented as resistance that is connected in series with the stator [46][47]. The effect of magnetizing saturation is taken into account in this model, because this kind of synchronous generator at full load is operating in non-linear regions [48].

The research contribution is to study the efficiency of PMSG accurately because of its benefits in the economic feasibility study, costs, design, and investigation of the performance assessment of PMSG-based wind turbine systems.

This paper includes four parts: the first one deals with the introduction, the second deals with the methods, whereas the third deals with the results and discussion, and finally the fourth part shows the conclusion.

II. METHODS

A. System Description

The PM rotor that has a suitable number of magnet poles when rotating at a suitable speed by prime mover as a hydro or wind turbine will have produced electrical output power on stator ends as shown in Fig. 1. The 1st part of this section contains the equations that are analyzing, representing, and modification of equivalent circuits to simplify the circuits that lead to reducing the differential equations without losing the accuracy of calculations [49][6][50]. Then, finding the mechanical and electromechanical torques and finally detecting the efficiency equation of PMG.

The 2nd part is a simulation setup of the model of a wind turbine that is connected to a permanent magnet synchronous generator by using a MATLAB Simulink environment. The MATLAB program is one of the best programs for simulating engineering systems, especially in the field of electricity and mechanics, as a result of its valuable and accurate equations, it is used in the research widely. This work focused on small-capacity wind turbines, which are generally designed for a wind velocity of 10-15 meters per second [51][52].

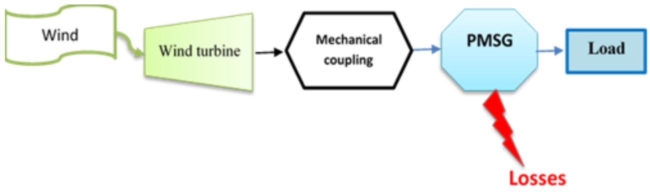


Fig. 1. The block diagrams

B. Mathematical Modeling Analysis

The mathematical model of permanent magnet synchronous generator (PMSG), for the power system and modify system analysis is as a rule the following assumptions: the stator are winding sinusoidal positioned along the air-gap as far as the alternate effect with the rotor involved; the slots of stator do not cause significant variations of the rotor inductance with rotor positioned; electrical losses, mechanical losses ,and saturation effects are considered; the windings stator is consider symmetrical; damping windings are considered; the wind speed is constant.

This part will analyze the generation system to its equations from the mechanical side and the electrical one, this analysis is useful to show the effect of performing and calculating the accurate efficiency of the recently increased PMSG in wind power, so the calculation of this efficiency contributes to the improvement of the renewable energy system. The major of the synchronous generator within the wind energy conversion systems WECSs is to convert rotating mechanical torque from the wind turbine as prime mover into generated electrical power so as to feed the loads in isolated areas. Below are the main equations that are necessary for calculating the PMSG's efficiency. By using Park's transformation matrix from three parameters ABC into two parameters d_{qo} (direct & quadrature axis) [53]. The mathematical equations for an open-winding three-phase PMSG are obtained, in which the stator voltages V_{abc} are transferred into the rotating reference frame V_{dq} in order to simplify the calculations such as in Fig. 2. which shows the d-q rotating frame; whereas θ is the angle between a-axis and d-axis [29][54].

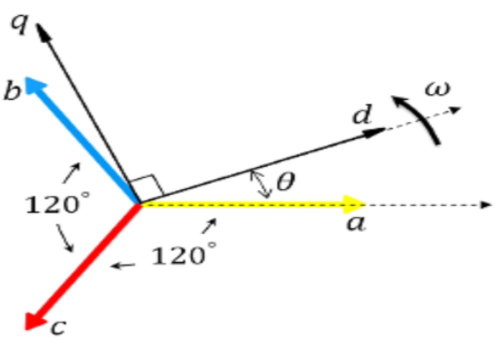


Fig. 2. Three-phase and rotating reference frame

Fig. 3 shown below represents the equivalent circuit of the permanent magnet synchronous generator (PMSG) in the DQ- axes reference frame [55][56]:

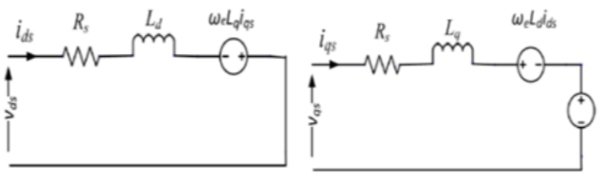
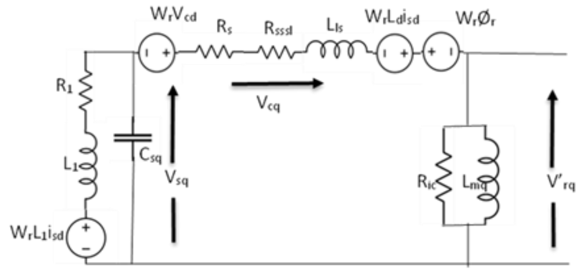


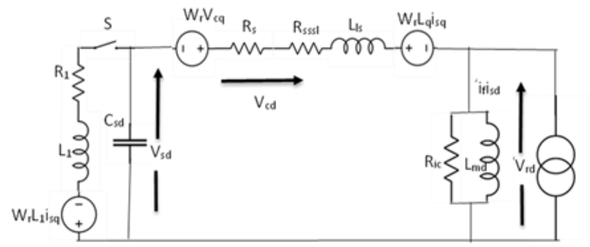
Fig. 3. The equivalent circuits of the PMSG in DQ-axes

C. Equations and Circuit Representation

Fig. 4 shows the PMSG equivalent circuit per phase of the D_Q axes rotation frame with the load inductive, taking into account the effects of each iron core loss and stray losses of the machine, where represented the losses of iron core by equivalent iron core resistance (R_{ic}) which is connected in parallel with magnetic inductance, while the losses of stray load represented as resistance ($R_{sss\ell}$) insert in series with the stator circuit [6][57][58].

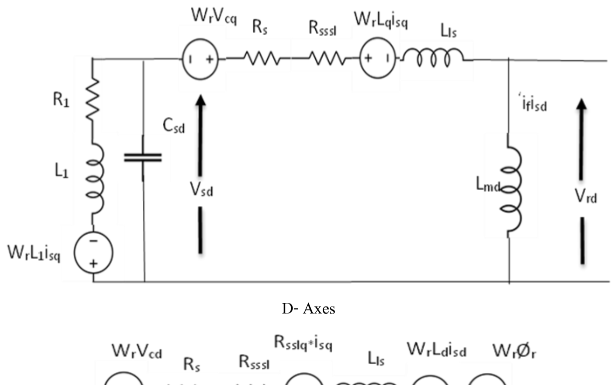


D-axes

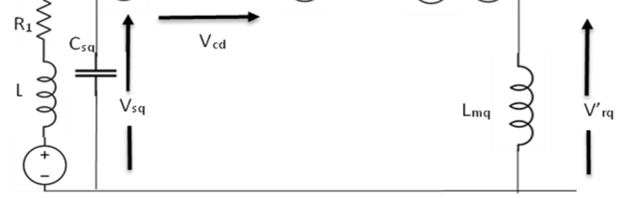


Q-Axes

Fig. 4. D-Q equivalent circuit of PMSG



D- Axes



Q- Axes

Fig. 5. D-Q axis equivalent circuits of PMSG modification

Fig. 5 showed the D-Q axes for modification of the PMSG. This circuit includes replacing the iron core (R_{ic}) resistance with series resistance and reflecting as a voltage drop in the stator circuit [59]. The magnetizing inductance (L_{MD} and L_{MQ}) in the D-Q axes are also modified [49]. In D-Q axes paradigm can be obtained from the equation (1) to (5) after modifying the iron core resistance (R_{ssicd} and R_{ssicq}), and the magnetizing inductance (L_{mq} & L_{md}) [60][23].

$$\begin{bmatrix} Vd \\ Vq \\ Vo \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\,(\theta) & cos\,(\theta-\frac{2\pi}{3}) & cos\,(\theta+\frac{2\pi}{3}) \\ -sin\,(\theta) & -sin\,(\theta-\frac{2\pi}{3}) & -sin\,(\theta-\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{1}$$

$$R_{ssicd} = R_{ic} \times w_r \times L_{Md} / [R_{ic}^2 + (w_r \times L_{Md})^2] \tag{2}$$

$$R_{ssicq} = R_{ic} \times w_r \times L_{Mq} / \left[R_{ic}^2 + \left(w_r \times L_{Mq}\right)^2\right] \tag{3}$$

$$L_{md} = L_{Md} \times R_{ic}^2 / [R_{ic}^2 + (w_r \times L_{Md})^2] \tag{4}$$

$$L_{mq} = L_{Mq} \times R_{ic}^2 / \left[R_{ic}^2 + \left(w_r \times L_{Mq}\right)^2\right] \tag{5}$$

Where, R_s is the stator phase resistance (Ω), W_r is the rotor speed in electrical (rad/sec.), L_{Md} is the D-axes magnetizing inductance/phase, L_{Mq} is the Q-axes magnetizing inductance/phase, R_{ic} is the iron core resistance gained from the no-load test as in the equation (6) [8][59][61].

$$R_{ic} = V_o / [Pnl - I_O^2 \times (R_s + R_{SSS\ell})] \tag{6}$$

The voltage in the D-Q axes of the rotor and stator of PMSG with parallel capacitance and inductive load derived from the modified circuit as in the equation (7) and (8).

$$C_{sd} = 1/[w_r^2 \times (L_{Md} + L_{\ell s} + L_\ell)] \tag{7}$$

$$C_{sq} = 1/\left[w_r^2 \times \left(L_{Mq} + L_{\ell s} + L_\ell\right)\right] \tag{8}$$

Where, L_ℓ is the load inductance/phase, in the case of using a round or cylindrical kind of rotor as in the equation (9) and (10).

$$L_{Md} = L_{Mq} = L_M \tag{9}$$

$$C_{sd} = C_{sq} = C_s \tag{10}$$

The voltage in the D-Q axes of the stator and rotor of PMSG with parallel capacitance and inductive load derived from the modified circuit of as in the equations (11) to (18).

$$V_{sd} = -v_{cd} - R_s \times i_{sd} - R_{sss\ell} \times i_{sd} - R_{ssicd} \times \left(i_f - i_{sd}\right) + w_r \times L_q \times i_{sq} - L_d \times \frac{di_{sd}}{dt} \tag{11}$$

$$V_{sq} = -v_{cq} - R_s \times i_{sq} - R_{ssss\ell} \times i_{sq} - R_{sssicd} \times i_{sq} - w_r \times L_d \times i_{sd} + w_r \times \acute{\emptyset}_r - L_q \times \frac{di_{sq}}{dt} \tag{12}$$

$$\acute{v}_{rd} = w_r \times \acute{\emptyset}_r - i_{sd} \times L_{md} \tag{13}$$

$$\acute{v}_{rq} = -w_r \times L_{mq} \times i_{sq} \quad (14)$$

$$v_{cd} = \int \left(\frac{i_{sd}}{c_{sd}} + w_r \times v_{cq} \right) dt + V_{cdo} \quad (15)$$

$$v_{cq} = \int \left(\frac{i_{sq}}{c_{cq}} + w_r \times v_{cd} \right) dt + V_{cqo} \quad (16)$$

$$\Psi_{sd} = -L_{ls} \times i_{sd} + (i_f - i_{sd}) \times L_{md} = -L_d \times i_{sd} + \acute{\emptyset}_r \quad (17)$$

$$\Psi_{sq} = -(L_{ls} + L_{mq}) \times i_{sq} = -L_q \times i_{sq} \quad (18)$$

Where, v_{sd}, v_{sq}, i_{sd}, and i_{sq}, is the stator phase voltages and currents in D-Q axes respectively, $\acute{\emptyset}_r$ is the permanent magnet flux per phase is referred as to the stator circuit. Can be seen in equation (19).

$$i_{f=}\ \acute{\emptyset}_r / L_{md} \quad (19)$$

$L_d = (L_{ls} + L_{md})$ is the stator d-axes self-inductance, $L_q = (L_{ls} + L_{mq})$ is the stator q-axes self-inductance. For round rotor machine $L_d = L_q = L_s$. The stator phase voltage r.m.s can be gained such as (20).

$$V_{ph} = [v_{sd}^2 + v_{sq}^2]^{\frac{1}{2}} / \sqrt{2} \quad (20)$$

The phase voltage components v_{sd} & v_{sq} in the case of resistive–inductive load can be calculated as (21) and (22).

$$v_{sd} = R_l \times i_{sd} + L_l \times \frac{di_{sd}}{dt} - w_r \times L_l \times i_{sq} \quad (21)$$

$$v_{sq} = R_l \times i_{sq} + L_l \times \frac{di_{sq}}{dt} + w_r \times L_l \times i_{sd} \quad (22)$$

Where, L_1 and R_1 inductive and resistance load per phase. The phase current of the stator (i_{sd} & i_{sq})and their derivatives in first-order differential. Equations can be gained from equation (21) and (22) such as (23) and (24).

$$\frac{di_{sd}}{dt} = (1 / Ld) \times [-vsd - vcd - (Rs + Rsssl) \times isd - Rsscid \times (if - isd) + w_r \times Lq \times isq] \quad (23)$$

$$\frac{di_{sq}}{dt} = (1 / Lq) \times [-v_{sq} - v_{cq} - (R_s + R_{sssl} + R_{ssciq}) \times i_{sq} - w_r \times L_d \times i_{sd} + w_r \times \acute{\emptyset} r] \quad (24)$$

D. Torque Calculations

The calculates of electromagnetic torque gained by the PMSG from the simplified equation (25) [62].

$$T_e = \left(\frac{3}{2}\right) \cdot (P_p) \times [\acute{\emptyset}_r \times i_{sq} - (L_d - L_q) \times i_{sd} \times i_{sq}] \quad (25)$$

The electromagnetic torque for this type of generator is sinusoidal [63]. In the case of the cylindrical rotor or round machine, the torque becomes as in the equation (26) [6][64].

$$T_e = \left(\frac{3}{2}\right) \cdot (P_p) \times \acute{\emptyset}_r \times i_{sq} \quad (26)$$

Where, P_p is the magnetic pole pairs, T_e is the electromagnetic torque (N.m), i_{sq} and i_{sd} is the stator phase currents. And $\acute{\emptyset}_r$ is the flux per phase that is gained from the permanent magnet toward the stator circuit. The alternator's mechanical speed (w_m) in radians per second can be calculated as (27) [18][65][66][67].

$$\frac{dw_m}{dt} = \frac{1}{J}(T_m - T_e - K_f \times W_m) \quad (27)$$

Where, J is the total moment of inertia in kg.m^2. T_m is the torque generated by the prime mover in N.m, K_f is the friction coefficient (N.m/(rad./sec.)), w_m is the mechanical speed of the alternator in radians/second. The type of machine is designed to rotate at a rated speed of 20-200 r/min, depending on the rated power of the generator [68].

E. Generator Efficiency Calculation

The rotor speed in electrical units (radians per second) can be calculated as (28) [6].

$$W_r = P_p \times W_m \quad (28)$$

The generator input power can be obtained (29) [45].

$$P_{in} = T_e \times W_m \quad (29)$$

Calculated the generator output power delivered to the load from (30) [61].

$$P_{out} = P_{in} - 3 \times I_{ph}^2 \times (R_s) \quad (30)$$

Where, I_{ph} is the phase current at load and can be obtained (31).

$$I_{ph} = (i_{sd}^2 + i_{sq}^2)^{\frac{1}{2}} / \sqrt{2} \quad (31)$$

On the other hand, the load active and reactive power can be calculated as (32) and (33) [69].

$$P_\ell = \left(\frac{3}{2}\right) \times (v_{sd} \times i_{sd} + v_{sq} \times i_{sq}) \quad (32)$$

$$Q_\ell = \left(\frac{3}{2}\right) \times (v_{sq} \times i_{sd} - v_{sd} \times i_{sq}) \quad (33)$$

The load power factor (P.F.) can be calculated as (34).

$$P.F. = P_\ell / [P_\ell^2 + Q_\ell^2]^{\frac{1}{2}} \quad (34)$$

The efficiency of the generator PMSG (η) can be calculated as (35).

$$\eta\% = \frac{P_\ell}{(P_{in} + P_{rot})} \times 100 \quad (35)$$

Where, P_{rot} is the total mechanical (rotational) losses for the generator and prime mover.

F. PMSG Parameters and Simulation Setup

The PMSG dynamic simulation pattern is established in Matlap at synchronous speed with the parameters: 3-phase, 230 V per phase, type of rotor is round, load resistance 25 Ω; Base power of the electric generator $8.5 \times (10)^3$ V.A with the following specifications:

Pp = 5; Rs = 0.425Ω; Kf = 0.0118N.m/(rad/sec); Ld = Lq = 0.000395H; Jg = 0.01197Kg; Ǿ = 0.433weber/phase. According to the above equation of the PMSG, we design the diagram depending on the parameters mentioned above in Fig. 6 by using Matlab/Simulink.

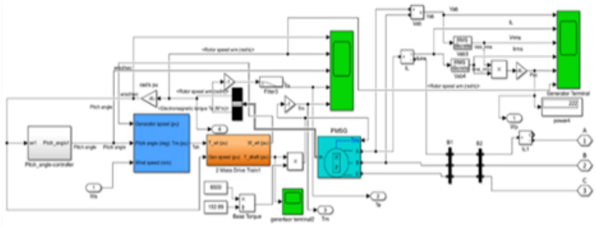


Fig. 6. Matlab Simulink –diagram of PMSG

Compared to other types of generators, PMSG, is more efficient due to its fixed magnet for generating the rotor flux.

III. Results And Discussion

The system proposed that the constant wind speed is 12 and 14 meters per second and the load is resistive, then run the system in Fig. 6 MATLAB 2020A, at the stop, time is five minutes to calculate the PMSG efficiency. Efficiency is calculated depending on the parameters of PMSG mentioned above and from the scope and meters to measure the electrical variables as shown in the curves and values for each wind speed.

A. The PMSG Efficiency at a Wind Speed 12 Meter per Second (Rated Speed)

As shown in Fig. 7 we notice the result of PMSG efficiency is 97.86% at steady state which means the PMSG is not affected a lot by the losses due to it having magnet property for the rotor flux. While Fig. 8 shows the electrical variables where the output voltage and currents are smooth and fixed from the amplitude side and frequency without harmonic also the output active power stays stable, while the power factor is unity because the load is resistive, while the reactive power is zero, due to no inductive load, also the output voltages and current are smooth and fixed from side amplitude and without harmonic frequency as shown in Fig. 9.

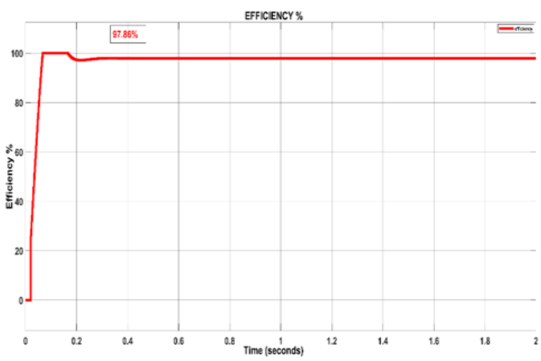


Fig. 7. The Matlab simulation efficiency for PMSG

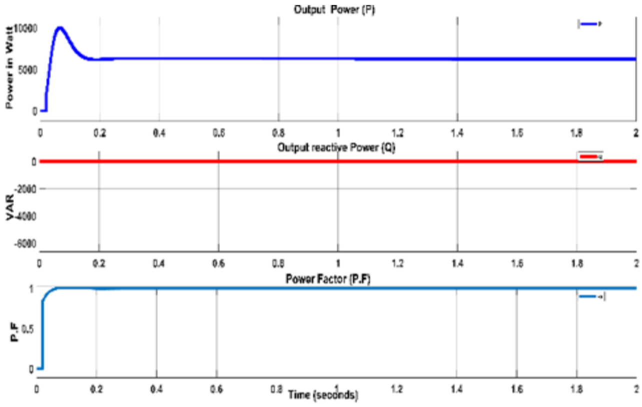


Fig. 8. Matlab results of electrical parameters

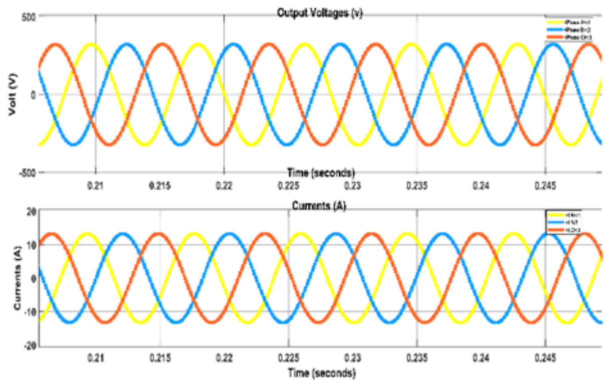


Fig. 9. Simulation output voltage and current

B. The PMSG Efficiency at a Wind Speed of 14 Meter per Second

From the simulation results of the proposed system at the speed of wind at 14 meters per second we notice the PMSG efficiency is 97.91% as shown in Fig. 9. This efficiency is higher than the first case at a wind speed of 12 meters per second where this demonstrates that the speed of wind has an effect on the efficiency with rate 0.05%, although this percentage is considered low, it is considered to change percentage and can be maximized in future work. There is very little difference in the increase in wind speed. While Fig. 10 shows the electrical variables, time in seconds the power factor is unity due to the resistive load, and the reactive power is zero due to absence the inductive, also from the Fig. 12 we notice that the simulation output voltages and current fixed from the magnitude side and without harmonic from frequency side at time in second that mean the PMSG has good performance in output voltages and currents.

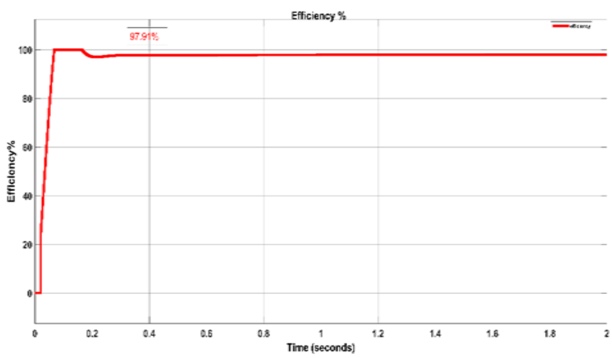


Fig. 10. The matlab simulation efficiency for PMSG

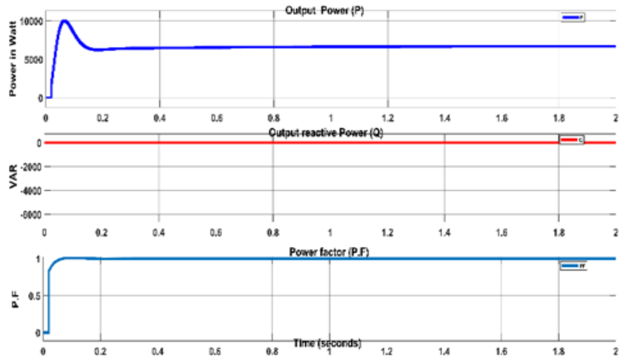


Fig. 11. Simulation electrical parameters

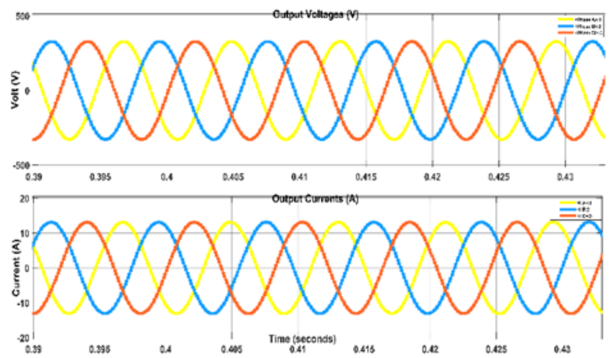


Fig. 12. Simulation output voltage and current

TABLE I. RESULT OF THE SIMULATION

Wind speed	Efficiency	Change Rate
12 m/sec.	97.86%	High efficiency at rated speed
14 m/sec.	97.91%	0.05%

C. *Summary of Results Discussion*

From the previous Table I, it is clear that the generator has high efficiency (97.86% at 12m/sec. and 97.91% at 14m/sec.) and that the percentage of losses is very low. Theoretically, neglecting the losses, the PMSG efficiency is 100%. Also, the wind speed has a small effect on the PMSG efficiency and this result is consistent with what was stated in the study efficiency of the PMSG within a range of wind speeds (12-14)m/sec., as its value reached 97% [70], and partly disagree with what was stated in the study at variable wind speed(8-10)m/sec.the PMSG efficiency was within limits of 91% [71], and the reason difference is due to the selection of variable and irregular speeds of wind speeds. The results of this paper are consistent with the efficiency of the permanent magnet motor, which was valued 96% [72]. Also, agree with the results of this paper with the efficiency of the permanent magnet machine that valued at 96% [73]. Finally, the overall efficiency of PMSG is very high compared to the efficiency of the induction generator, which ranges to 80-85%, because the losses in it are high, especially iron losses [74]-[78].

IV. CONCLUSION

In this work, the PMSG machine model was dealt with and calculated the effect of iron losses and stray load losses on the efficiency of the machine, taking into consideration that the differential equations of this model do not increase. The stray load losses were represented as a resistance connected in series with the stator circuit, while the iron core losses were represented by resistance reflected as a drop voltage in the circuit. The equivalent circuit of the PMSG has been modified to deal with all elements of the machine in the course of maintaining the accuracy of the performance of the machine. This paper also employs the effect of wind speed on efficiency.

The simulation results showed that efficiency is very high 97.86% and was not strongly affected by the very few losses and at two different wind speeds. This high efficiency of PMSG can contribute to maximizing power output, reducing energy waste, improving the overall performance of renewable energy systems, reducing maintenance costs, increasing the lifespan of the system, economic feasibility, and improving the power quality.

V. FUTURE WORK

For enhancing the performance and maximizing the efficiency of the PMSG, authors may wish to use a resistive, inductive, and capacitive load together to achieve resonance conditions when operating at synchronous speed to get high output power in future work.

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