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Original Article

Design Analysis of Intelligent Controller to Minimize Power Loss of Grid Connected Wind Energy Conversion System

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Abstract *- This paper focuses on the power loss study of the Simulink model of the wind-driven Permanent Magnet Synchronous Generator System and the study of all five types of wind energy conversion turbine systems. Its various outputs were studied for the wind speed of range 6 m/s to 14 m/s. The case has been studied for minimum power losses at optimal speed. This paper will be helpful for the research scholars to provide a broad understanding of PMSGS for various engineering applications. A classified list of 34 publications on this topic is also given for quick reference.*

Keywords *- Wind Energy Conversion Turbine System (WECTS), Synchronous Generator (SG), Permanent Magnet Synchronous Generator System (PMSGS), Squirrel Cage Induction Generator System (SCIGS), Wound Rotor Induction Generator System (WRIGS).*

1. Introduction of Wind Energy Scenario across the World

1.1. Wind Energy in India

With energy concerns, wind plays a wider role in developing energy in India, making it the fifth-largest wind market in the world and economically rich. A long belt of India touches the seashore, making it rich as a wind energy source. For the development of the country, renewable energy plays an important role.[1][2]

1.2. Installed Wind Energy Capacity in India

The wind is a renewable energy become a common source in India. Here the state-wise table and bar chart are given for wind energy installed capacity in India. India is producing 42.63 GW of energy as per the data of march 2023. [1, 2]

2. Configuration of Wind Energy Turbine Systems

2.1. Configuration 1: Fixed Speed Type Wind Energy Conversion Turbine System

In configuration 1, the generator is coupled to the grid system with the help of a soft starter. This is the oldest one, as shown in Figure 2 [3, 4].

Advantages:
a) Most Reliable
b) Initial Cost Low
c) Simple in construction

Disadvantages:
a) Low conversion efficiency
b) Additional hardware required
c) During grid faults, severe mechanical stress occurs
d) Grid voltage fluctuates with the variation in wind speed [4]

2.2. Configuration 2: Semi Variable Speed Type Wind Energy Conversion Turbine System

Configuration 2 uses a rotor resistance mechanism and is a semi-variable speed type system. A diode rectifier and chopper are used to make it. The wind's Variable Speed (11%) is transferred to the turbine's rated speed by adjusting the rotor resistance. [5-7] As depicted in the illustration, this approach uses variable rotor resistance. A wound rotor induction generator system (WRIGS) is used with this turbine.

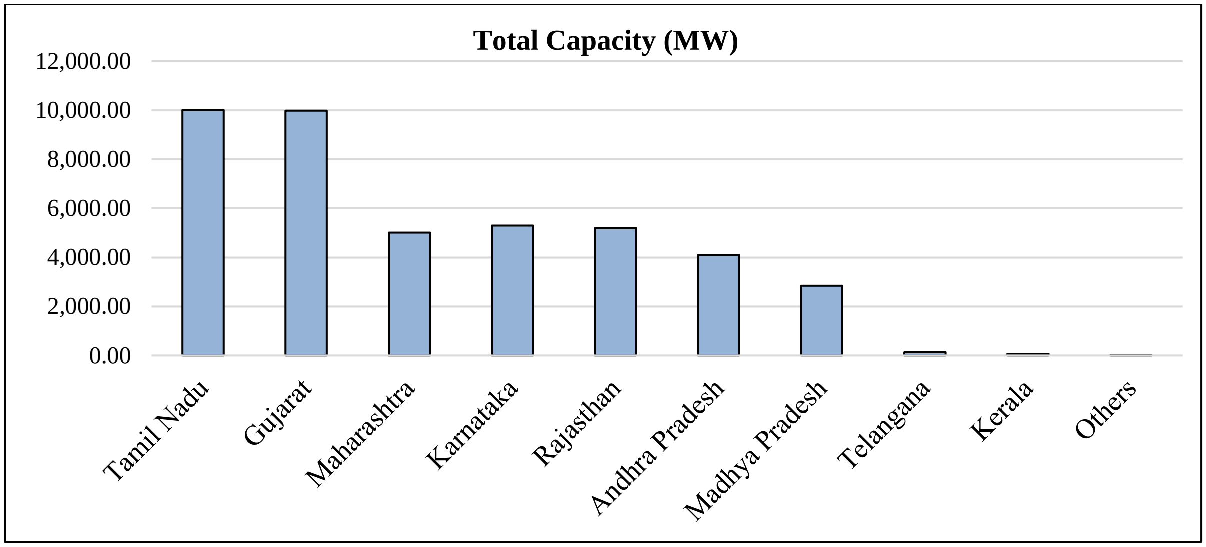

Fig. 1 Installed wind energy capacity in India (31 March 2023)

Advantages:
a) Increase the lifespan
b) Mechanical stress reduced
c) Low maintenance required
d) Energy conversion efficiency increase

Disadvantages:
a) Cost increase
b) Rotor resistance losses
c) Limited speed of operation
d) Rotor resistance variable switch

2.3. Configuration 3: Semi Variable Speed Type Wind Energy Conversion Turbine System

In Configuration 3, this configuration is commonly used in the current scenario in the wind world. DFIDS is used as a conversion system.[8] This DFIGS system is shown in Figure 4.

Advantages:
a) Robust in nature
b) Dynamic performance improved
c) Modified turbine for extended speed

Disadvantages:
a) Coupling Capacitor is required
b) Low brushes life (6-12 months only)
c) Faults due to limited rated power converters

2.4. Configuration 4: Full Variable Speed Type Wind Energy Conversion Turbine System

It is a full variable speed type wind energy conversion turbine system. [9, 10]. The hundred percent rating of power electronic components (converters) plays a big role in the following ways:

- Cost increases
- Handle reactive power
- Circuit become complex
- Smooth grid connection
- The size of the machine increases

The system is shown in Figure 5.

Advantages:
a) Highly robust
b) High efficiency
c) FRT compliance is good

Disadvantages:
a) High cost
b) Complexity increase
c) High Power converter losses

Table 1. Installed wind energy capacity in India (31 March 2023)

State	Total Capacity (MW)
Tamil Nadu	10,017.18
Gujarat	9,978.92
Maharashtra	5,012.84
Karnataka	5,294.96
Rajasthan	5,193.42
Andhra Pradesh	4,096.66
Madhya Pradesh	2,844.29
Telangana	128.14
Kerala	62.5
Others	4.31
Total	42,633.22

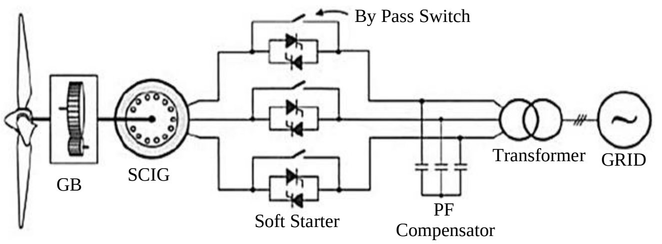

Fig. 2 Configuration 1: WEC Turbine System with Fixed Speed

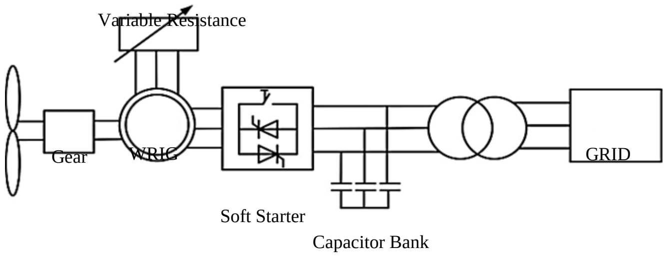

Fig. 3 Configuration 2: WEC turbine system with semi variable speed

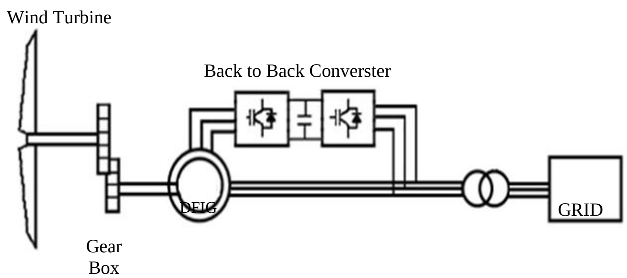

Fig. 4 Configuration 3: WEC turbine system with semi variable speed

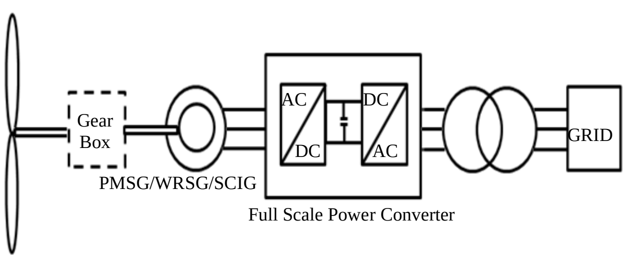

Fig. 5 Configuration 4: WEC turbine system with full variable speed

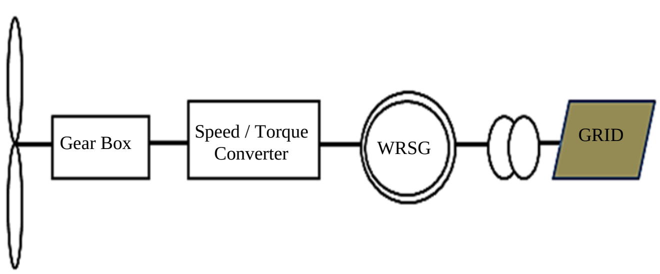

Fig. 6 Configuration 5: WEC turbine with full variable speed

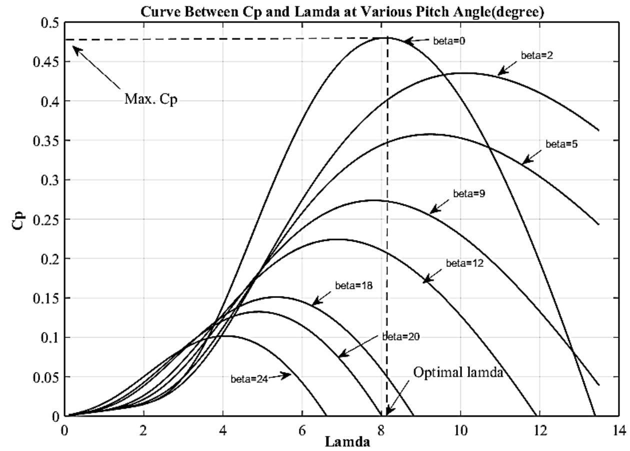

Fig. 7 Cp and λcurve (λ= tip speed ratio for different pitch angles)

2.5. Configuration 5: Full Variable Speed Type Wind Energy Conversion Turbine with WRSG

In this configuration electrical converter is replaced with a mechanical converter. This automatic converter operates the wind turbine to achieve the desired wind speed by its variable nature. [11, 12] The generated voltage is directly given to the grid (Figure 6).

Advantages:
a) Low cost
b) High efficiency
c) Easy to operate

Disadvantages:
a) Mechanical stress problem
b) Complex in hardware
c) Mechanical converter required

3. Mathematical Representation of Wind Energy and Turbine Energy

A wind turbine extracts the kinetic energy from the blades of the turbine rotating with low speed through the flow of wind and converts the same into energy by the system (WECS). [13] The formula used is given below.

$$P_{wind} = 0.5\rho_{air}\pi R^2 V_{wind}^3 \quad (1)$$

Where,

P_{wind}=Wind power
ρ_{air}=1.225 Kg/m^3(air density approximately)
R=Radius of wind turbine blade
V_{wind} = speed of wind in m/s.
ω= rotational speed of wind turbine
Cp = Value given by the manufacturers

$$T_m = P_m/\omega_{turb} \quad (2)$$

4. Permanent Magnet Synchronous Generator

4.1. PMSG

It is clear by name that permanent magnets generate the rotor magnetic flux of PMSG. Generally, these are brushless generators.[14] Windings are absent on the rotor. Due to the absence of the rotor windings following can be achieved.[15]

- High power density
- Small in size
- Less material required
- Low cost of the generator
- Zero rotors winding loss
- The thermal stress of the rotor reduces

On the other hand, the drawbacks of these generators are given below:

- Permanent magnets are expensive
- Prone to demagnetization [16]

4.2. Mathematical Modeling of PMSG System

The analysis of PMSGS becomes easy with the help of the axis model. The SG is modelled in the reference frame and rotor field in the desired output.[17] The dq-axis model of the stator circuit is too much similar in basics to the induction generator, so we take the conversion of that and run it, except the following:

(a) Induction generator speed is represented by ω for a given reference frame. It is modelled (replaced) to obtain the desired output of the system by the rotor speed ωr in the synchronous frame.
(b) Magnetizing inductance is represented by Lm. Lm is replaced by the dq-axis Ldm magnetizing inductances and Lqm of the synchronous generator. In a non-salient Synchronous Generator.[18]
(c) For the d- and q-axis, magnetizing inductances (Ldm = Lqm) are equal.
(d) On the other hand, in the case of a salient pole-type generator magnetizing inductance for the d-axis is slightly more than q-axis (Ldm<Lqm).
(e) Following are the outward stator currents. These currents (dq-axis), ids, and iqs flow out of the stator. This action is named a generator convention. This is only why most synchronous machines are used as an alternator.[19]

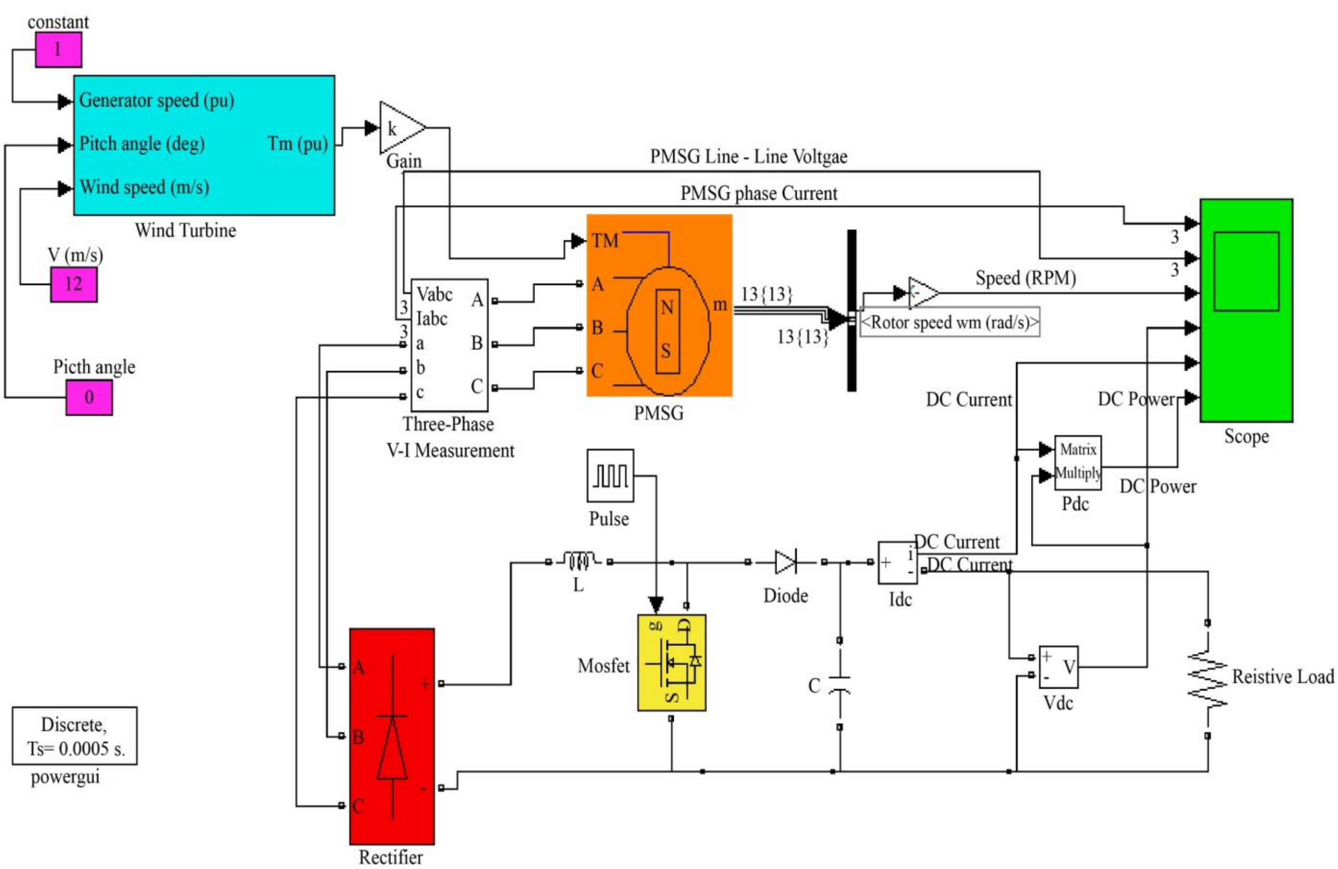

Fig. 8 MATLAB model of wind-driven PMSG system

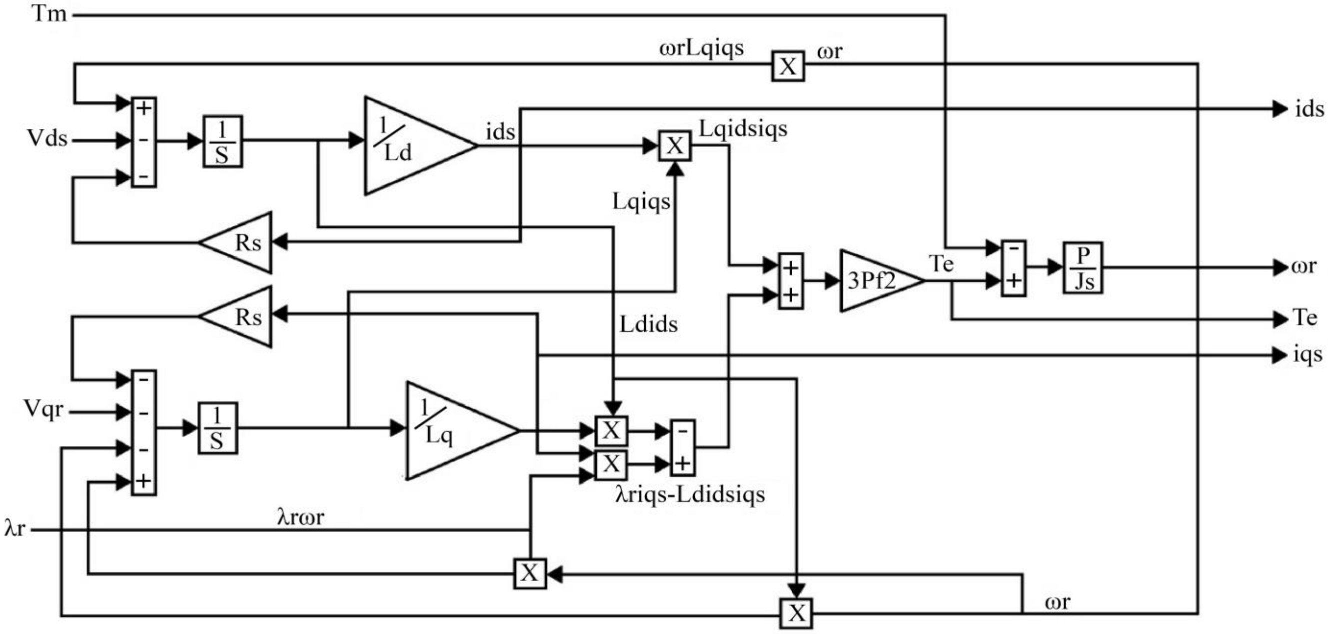

Fig. 9 Block diagram of synchronous generators (SG) simulated with MATLAB

For the simplification of the Synchronous Generator model, the following assumptions are made:

- Mathematical manipulations can be incorporated.

The equations of voltage for the calculation of Vdsfor synchronous generator are given below:

$$Vds = -Rs * ids - \omega r * \lambda qs + p * \lambda ds$$

$$Vqs = -Rs * iqs - \omega r * \lambda ds + p * \lambda qs$$

$$\lambda ds = -Lis * ids + Ldm(If - ids)$$

$$= -(Lis + Ldm)ids + Ldm * If - Ld * ids + \lambda r$$

$$\lambda qs = -(Lis + Lqm)iqs = -Lq * iqs$$

Where:

lambda-r is the rotor flux

Ld and Lq are the stator dq-axis self-inductance.

$$\lambda r = Lds * If$$

$$Ld = Lls + Ldm$$

$$Lq = Lls + Lqm$$

Substituting the above equation and considering d of lambda-r/dt= 0 when the field current is constant in the case of WRSG.

On the other hand, it is constant lambda-r in the PMSG system.

$$Vds = -Rs * ids - \omega r * Lq * iqs - Ld * p * ids$$

$$Vqs = -Rs * iqs - \omega r * Ld * ids + \omega r * \lambda r - Ld * p * iqs$$

A simplified model for the synchronous generators is given below, derived based on the above equations. About the same is given below:-

(a) The simplified mode of the wind system is too accurate and easy to operate. Once the assumption was made for the output calculation, assumptions were not changed during the calculation. Ideal and identical results are obtained during the analysis of the model. These results are based on a simulated model. [20, 21]

(b) The type of rotor used in the Synchronous Generator (SG) model is generally a wound rotor. Permanent-magnet type rotor is also used in some special cases. When the field current (I_f) is given for a particular value in the WRSG, we can now calculate rotor flux. [22, 23] formula used for the calculation of rotor flux is given below:

$$\text{Lambda-r} = Ldm\ I_f$$

Rotor flux is produced as per the pole strength of permanent magnets. [24, 25] Rated Value and other parameter constants are written on the head of the machine, i.e. nameplate. These values and other parameter constants are directly used in the formula for the calculation. [26-28]

(c) There are two types of poles one is salient, and the second one is non-salient. It is clear that the model applies to the salient pole of synchronous generators and non-salient-pole-type synchronous generators. Parameters for salient- and non-salient-pole type are as follows, [29-31] for a non-salient type generator, the dq-axis synchronous inductances, Ld is equal to Lq(Ld=Lq), whereas, Ldnot equal to Lq for salient pole type generator it means that Ld and Lq have different values. The d-axis synchronous inductance of PMSG is usually somewhat low in Value as the q-axis (Ld<Lq) and as per the demand. [32, 33]

The electromagnetic torque is developed by the Alternator (SynchronousGenerator). The same torque equations for the Induction Generator can calculate that for the result. These are given below,

$$\mathrm{Te} = \frac{3}{2}\mathrm{p}(\mathrm{iqs} * \lambda\mathrm{ds} - \mathrm{ids} * \lambda\mathrm{qs})$$

Or

$$\mathrm{Te} = \frac{3}{2}\mathrm{p}(\lambda\mathrm{r} * \mathrm{iqs} - (\mathrm{Ld} - \mathrm{Lq})\mathrm{ids} * \mathrm{iqs}$$

The rotor speed **ωr** is torque dependent equation, which is given below:-[34]

$$\omega\mathrm{r} = \frac{\mathrm{p}}{\mathrm{JS}} * (\mathrm{Te} - \mathrm{Tm})$$

For the SG model, dynamic simulation is given for synchronous generators, equations are rearranged as under:-

$$\mathrm{ids} = 1/S(-\mathrm{Vds} - \mathrm{Rs} * \mathrm{ids} + \omega\mathrm{r} * \mathrm{Lq} * \mathrm{iqs})/\mathrm{Ld}$$

$$\mathrm{iqs} = 1/S(-\mathrm{Vqs} - \mathrm{Rs} * \mathrm{iqs} + \omega\mathrm{r} * \mathrm{Ld} * \mathrm{ids})/\mathrm{Lq}$$

With the help of three equations simulated model of the SG/PMSG is resolved, and the output is calculated. Parameters [35] listed below are used as input of SG model, with the different values to get optimum output.

- Vds and Vqs= dq-axis stator voltages
- λr = Rotor flux linkage
- ꞇm = Mechanical torque

On the other hand, the following parameters are preferred on the output side.

- ids and iqs = dg-axis stator currents
- ωm = Rotor mechanical speed,
- ꞇe = Electromagnetic torque [36, 37]

5. Simulink Model of System

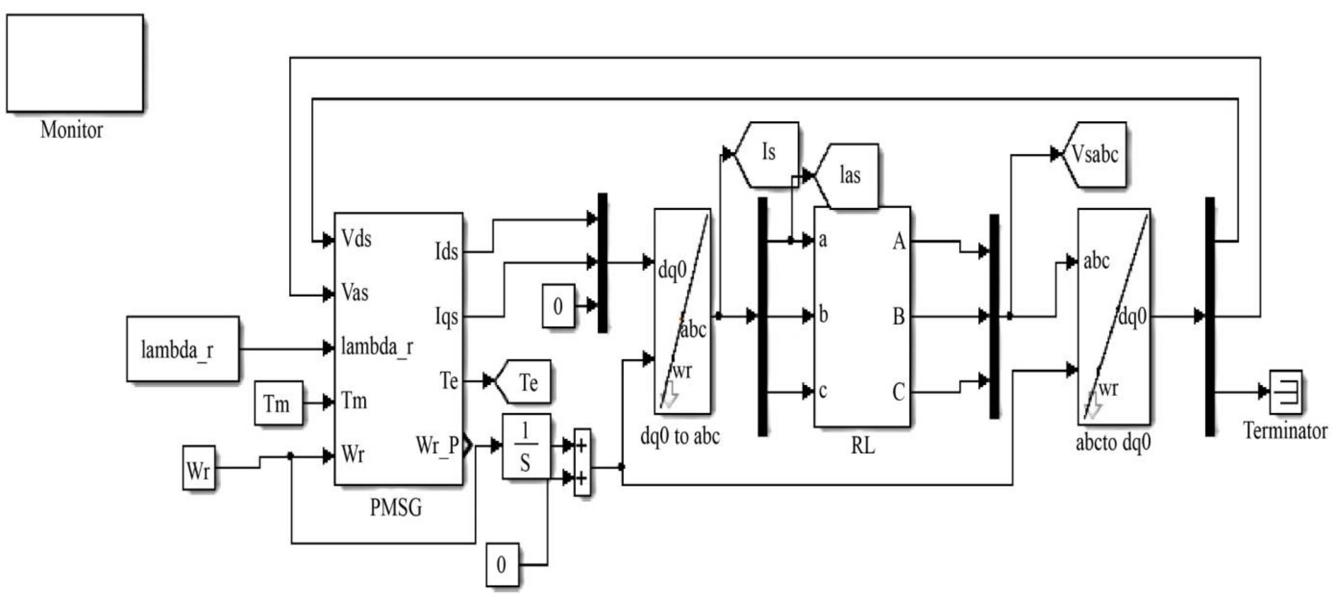

Fig. 10 Simulink model of PMSG with resistive load in standalone mode

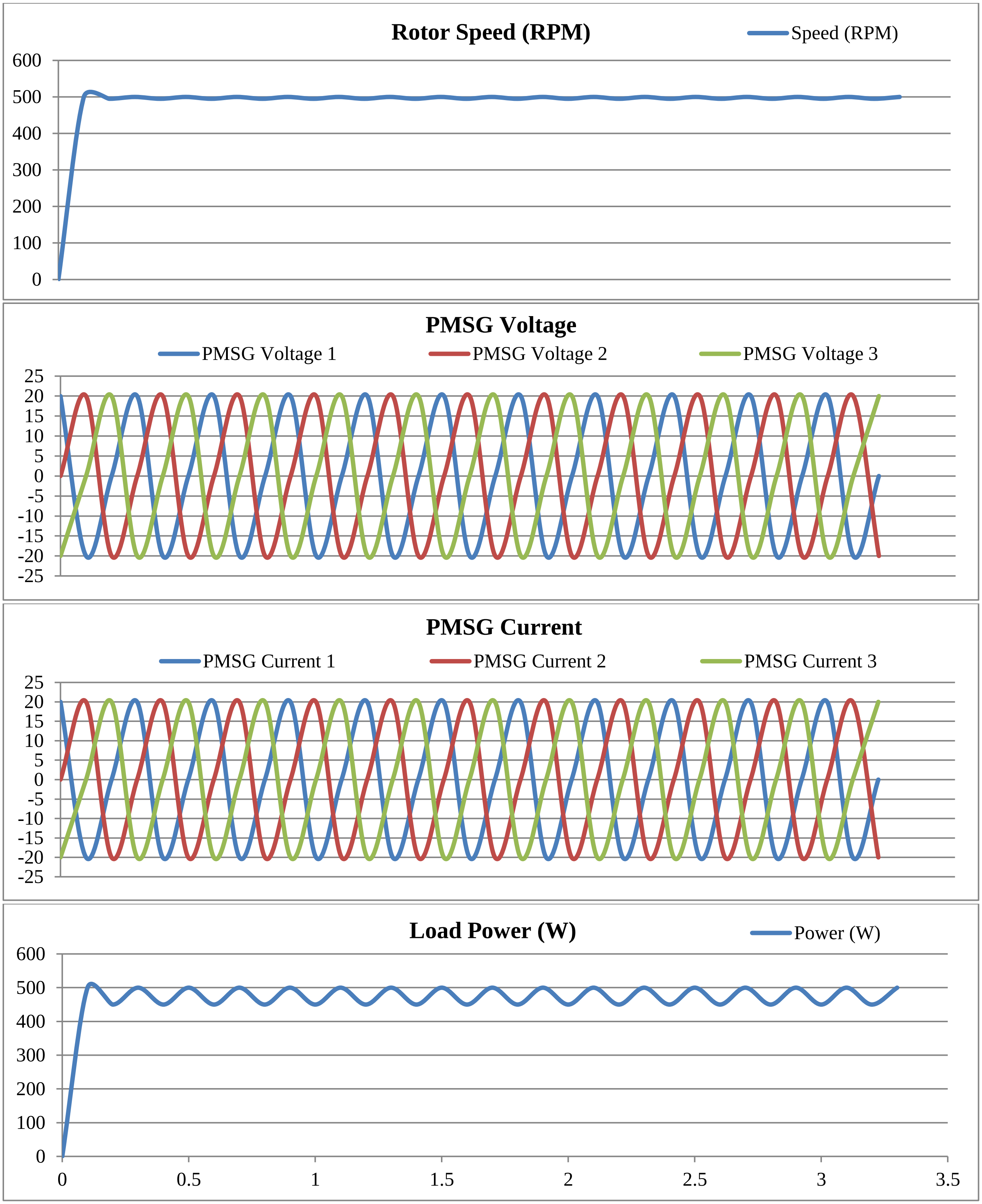

Fig. 11 Simulink output of PMSG system (as the speed of the rotor, current, voltage and load power at a constant speed of 11mps)

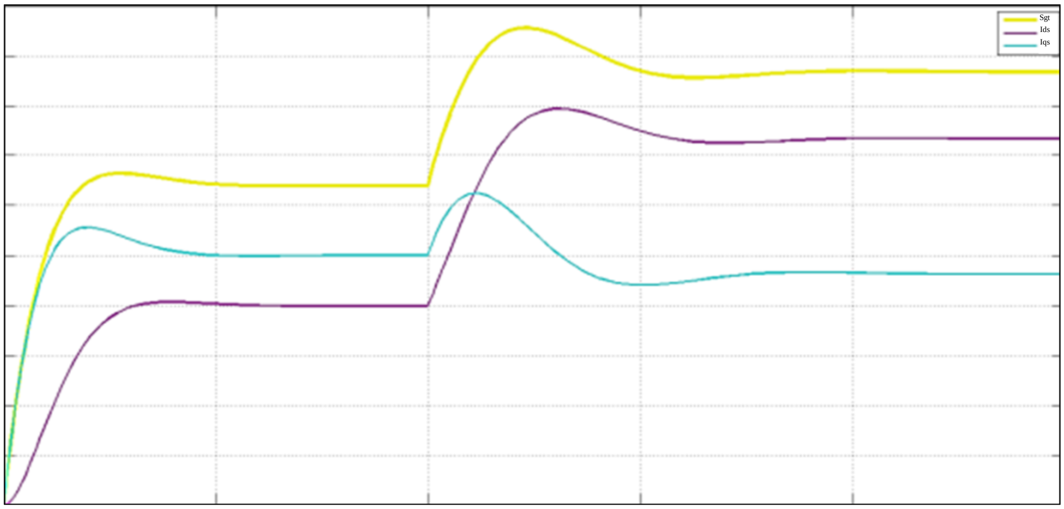

Fig. 12 Ids, Iqs and Is

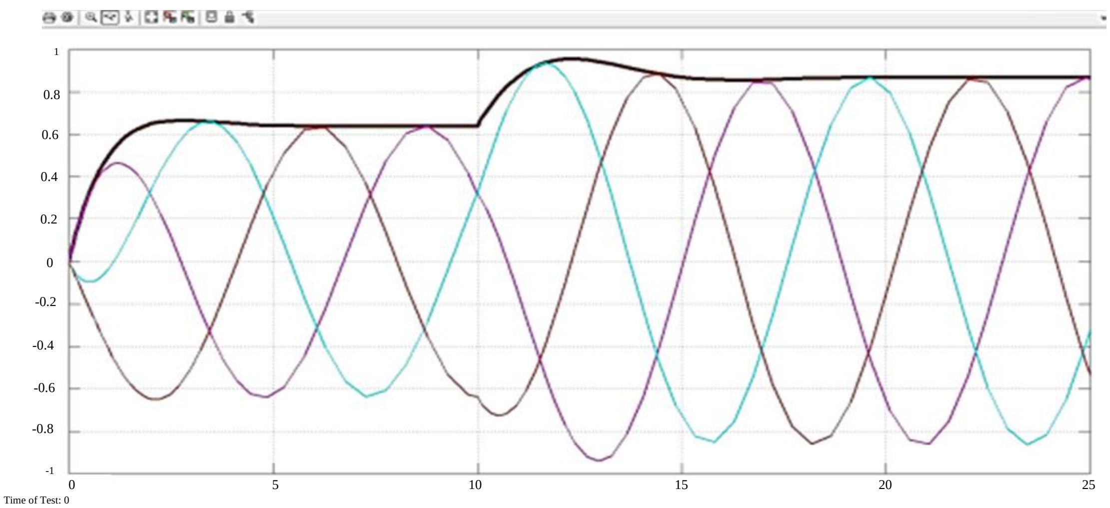

Fig. 13 Ias, Ibs and Ics

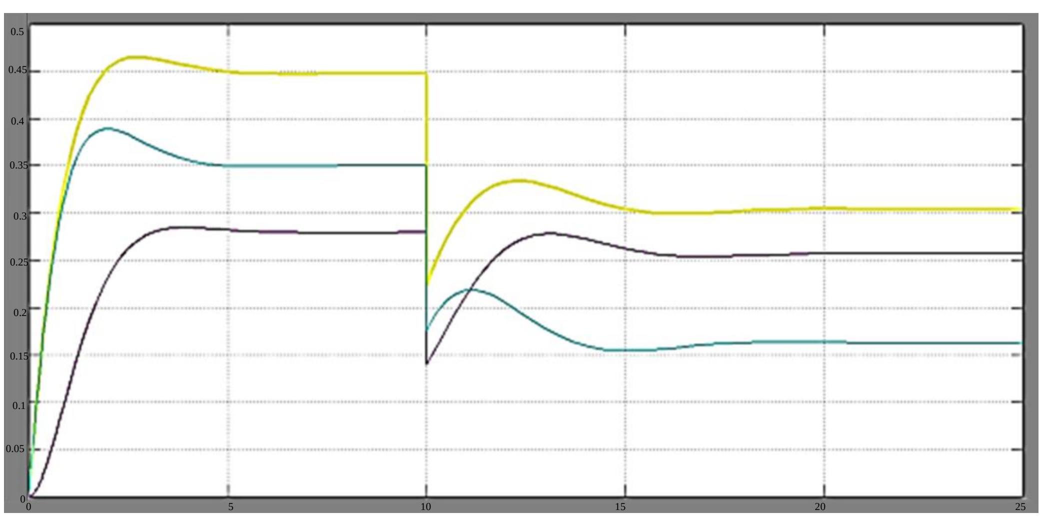

Fig. 14 Vs, Vas, Vbs and Vcs

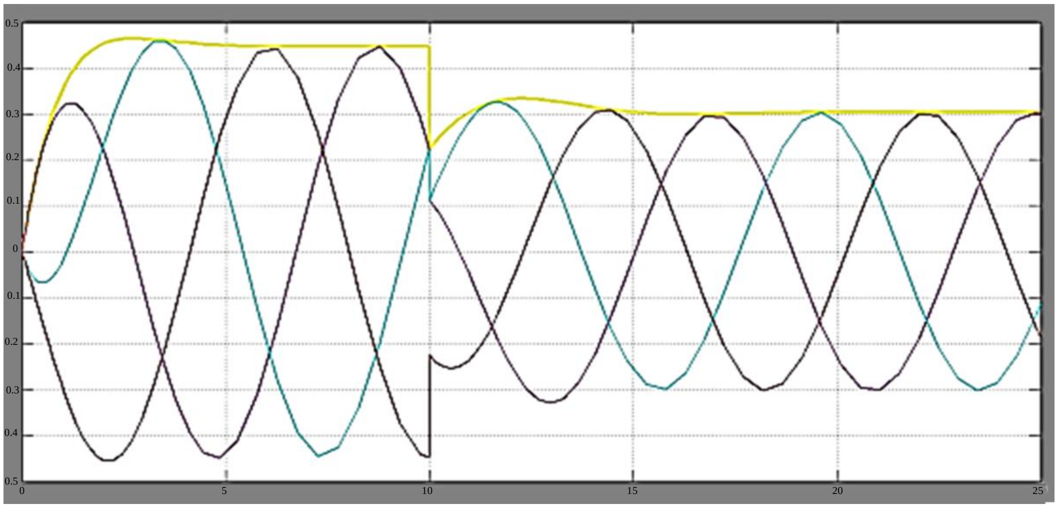

Fig. 15 Te and Ps

Table 2. Previous result of PMSGS (output parameters at different wind speed range) (6- 14 mps)

S. No.	Wind Speed (MPS)	Rotor speed (RPM)	Output voltage (VOLT)	Output current (AMPERE)	Developed Power (VA)	Useful Power (WATT)	Power Loss (WATT)
1	6	273.9	16.1	8.7	140.07	109.87	30.2
2	7	301.4	17.8	9.7	172.66	141.46	31.2
3	8	334.2	22.5	9.6	216	183.8	32.2
4	9	411	22.8	10.6	241.68	207.48	34.2
5	10	426	26.5	14.6	386.9	356.7	30.2
6	11	484.1	29.9	14.9	445.51	425.31	**20.2**
7	12	552.2	31.3	10.7	334.91	309.81	25.1
8	13	575.4	33.8	9.7	327.86	293.46	34.4
9	14	619.5	36.3	9.2	333.96	302.76	31.2

Table 3. Current result of PMSGS (output parameters at different wind speed ranges) (6- 14 m/s)

S. No.	Wind Speed (MPS)	Rotor speed (RPM)	Output voltage (VOLT)	Output current (AMPERE)	Developed Power (VA)	Useful Power (WATT)	Power Loss (WATT)
1	6	271.8	16.2	8.7	140.94	109.84	31.1
2	7	302.2	17.5	9.7	169.75	139.55	30.2
3	8	333.4	22.3	9.6	214.08	182.76	31.32
4	9	412.8	22.1	10.6	234.26	201.06	33.2
5	10	425.6	26.6	14.6	388.36	356.16	32.2
6	11	481.1	29.9	14.9	445.51	425.91	**19.6**
7	12	552.2	31.2	10.7	333.84	302.74	31.1
8	13	575.7	33.8	9.7	327.86	302.46	25.4
9	14	616.8	36.1	9.2	332.12	300.92	31.2

6. Results

6.1. Result of the Model

The result of the model is displayed on the screen of scope as current (A), voltage (V), rotor speed (RPM), load and power (WATT) at a windspeed of range 6 –14 mps.

7. Conclusion

The SG model is modified to act as PMSGS, and the post connecting it with resistive load and its various outputs were studied for the 6-14 mps wind speed range. This PMSGS model is studied in standalone operations. MATLAB/ Simulink environment is used for the simulation of the model.

The optimum result is obtained at 11 mps, i.e. 19.6 watt. Its results are compared with the latest update. These outputs were analysed and found correct and improved.

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