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Enhanced Performance of Isolated Wind-Diesel (IW-D) Hybrid System feeding Heavy Load under various Operating Conditions

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Abstract

Objectives: To check /validate the stiffness of IW-D Hybrid System by putting heavy load of 150 hp at various loading conditions. And, to implement the remedies to the ill-conditions/operating conditions like frequency runaway and varying wind speed and to study the effect of these conditions on overall system as well as on heavy load. Further, to improve system performance, a suitable controller is to be incorporated with pitch angle control system. **Method/Statistical Analysis:** The electromechanical dynamics of various large electrical machines are represented by their full order models. The models of synchronous machine (7th order) of diesel genset, SEIG (5th order) and heavy load (5th order) are simulated to obtain power and voltage dynamics. The system dynamics consist of higher order differential equations, which are solved by converting into simpler algebraic equations related to current and voltage that are solved in short time by using phasor simulation in MATLAB/Simulink environment. **Findings:** The hybrid power systems are becoming popular because of greater efficiency and balance of energy supply. Due to many advantages like ruggedness, inexpensiveness and requirement of less maintenance in contrast to other electrical machines, heavy load like 3-ϕ squirrel cage induction motor that shares a major part of the total electrical portion on any power system. From the exhaustive study of, it is found that very few authors have worked on such system and the performance of the heavy load is either not considered of if taken into account it is not considered in detail. In this paper, an IW-D Hybrid Power System feeding heavy load is considered to analyze/ check the stiffness of IW-D Hybrid System. Few ill-conditions like frequency runaway and varying wind speed affects the system functioning and have considerable impact on the heavy load is reported in few papers but its remedy is not implemented or if given, the ill effect of these problems on the heavy load is not considered which needs great attention. Therefore, the solutions of above problems are mentioned in this work. **Application/Improvement:** The dynamic performance of modified IW-D Hybrid System has been validated and checked in context with ruggedness by putting heavy load of 150 hp at normal and overload condition. The dynamic behavior of IW-D System as well as heavy load has been improved for frequency runaway. Further, a PI controller including pitch servo is implemented to control the output of SEIG driven by wind turbine in case of varying wind speed, which improves the dynamic performance of the system.

Keywords: Diesel Genset, Dummy Load, Excitation Capacitor, Heavy Load (3-Φ Squirrel Cage Induction Motor), Hybrid System, Isolated Wind-Diesel (IW-D) Self Excited Induction Generator (SEIG), Static Load

1. Introduction

The depletion of conventional resources has led to opt the non-conventional energy sources like wind, solar, etc. required for the generation of clean energy thereby reducing the level of pollution. Most of the developing countries rely on these resources because of its availability in abundance and in grid isolated areas[1,2].

The electrical energy harnessed from wind has been used since ancient times for various purposes such as water pumping in flour mills and for many other purposes. Wind is useful resource for power generation from

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the viewpoint that it is cheap, easily available in remote areas and does not cause any environmental problem which is its main advantage. The grid isolated areas are more benefited by connecting diesel generating units in parallel with wind generation thus ensuring continuity of supply[3–5].

The generation of electricity using wind turbines is suitable in remote areas which are generally grid isolated. Grid isolated power system is much advantageous over grid connected system because in grid connected systems, wind power generators should stay connected during the fault conditions to the grid according to grid codes which create disturbance in the wind turbines. The wind turbine may also get damaged due to the stress on rotor shaft because the electromagnetic torque oscillates at double the grid frequency[6,7].

A lot of work is going on in the area of FACTS devices[8] for reactive power compensation but there are many drawbacks of devices such as, it introduces harmonics in the power system which affect the sensitive equipments and also it deteriorates the performance of heavy loads connected in the power system, whereas diesel genset provides reactive power without such problems that are caused by FACTS devices[9,10].

The best suited generator for wind turbine energy generation in remote grid isolated areas is Self-Excited Induction Generator (SEIG) as they are less expensive, robust, have better transient performance and require low maintenance. A wind turbine drives the three-phase induction machine which is operated in self excitation mode by connecting a capacitor bank in parallel to its stator terminal[11–13]. The diesel generator consisting of synchronous generator and diesel engine will keep the balance of power supply when there is change in load and in speed of the wind which ultimately changes the wind turbine generation[14,15].

The loads are of different types such as industrial load or heavy loads like water pumps, compressors which are responsible for causing voltage and frequency fluctuations in power system. Other types of loads are domestic loads such as lighting, heating that do not get affected much by the disturbance in the power system. Another type of loads are electronic loads such as radar, television and many more that are much sensitive to disturbance in the power system[16]. Many authors have worked on the grid connected system but little work has been done on isolated Hybrid System feeding heavy load.

Many shortcomings like frequency runaway, variable wind speed have been raised, but no technical solution is implemented to overcome the mentioned problems. The impact of frequency runaway and variable wind speed on the diesel generator have not been taken into consideration. Further, the performance of heavy load has either not considered or if taken into account, it is not considered in detail during these ill-conditions[16,17].

In this paper, the performance of an IW-D Hybrid System is analyzed which is feeding heavy load (150 hp) used for water pumping or in industries. The local loads such as residential or light loads are also considered in the form of static load. The system performance and especially, the performance of heavy load under various loading conditions are assessed. The problem of frequency runaway is generated and its remedy to overcome this problem is discussed in this paper. Increased wind speed increases the output of SEIG which needs to be controlled by some suitable controller which is presented in detail[16–18].

2. System Modeling

The IW-D Hybrid System requires models of the following: 1. Wind Turbine; 2. SEIG; 3. Diesel Genset; 4. Heavy load and 5. Dummy load.

2.1 Modeling of Wind Turbine

The mechanical output power is given by[19,20].

$$P_{mech} = p_t(\lambda, \beta)\frac{\rho a}{2} v^3_{wt} \tag{1}$$

Where

Mechanical output power	=	P_{mech} in watts
Performance coefficient	=	p_t
Air density	=	ρ in kg per m^3
Pitch angle of blades of wind turbine	=	β in degrees
Area swept by blades	=	a in m^2
Speed of wind	=	v_{wt} in m per s
Tip speed ratio	=	λ

The performance coefficient of wind turbine is:

$$p_t(\lambda, \beta) = p_1\left(\frac{p_2}{\chi} - p_3\beta - p_4\right)e^{\frac{-p_5}{\chi}} + p_6\lambda \tag{2}$$

Where

$$\frac{1}{\chi}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{1+\beta^3}$$

and $p_1 = 0.50,\ p_2 = 116,\ p_3 = 0.40,\ p_4 = 5,\ p_5 = 21,\ p_6 = 0.0068$.

2.2 Modeling of 3-ϕ SEIG

The wind turbine drives the SEIG and the reactive power required for starting is provided by the shunt excitation capacitor bank. Several papers have already been published on the modeling of SEIG[21–24]. Therefore the mathematical modeling of SEIG is not considered in detail in this paper.

2.3 Modeling of Diesel Genset

The diesel genset consists of a prime mover i.e. diesel engine and synchronous generator. The diesel engine comprised of a governor and exciter shown in Figure 1. For keeping the frequency constant, the governor maintains the rotor speed constant by supplying the rated power. The governor of diesel genset maintains the balance of real power in the system. The synchronous generator with exciter provides output voltage control which is affected by the time constant of field winding, DC power supplied to the field winding and its response. The excitation control system maintains the balance of reactive power thereby controlling its output voltage[25].

As the wind speed and load never remains constant therefore frequency and its voltage will not remain constant under transient conditions, thus the diesel genset will follow change in wind speeds and loads[14,15,26].

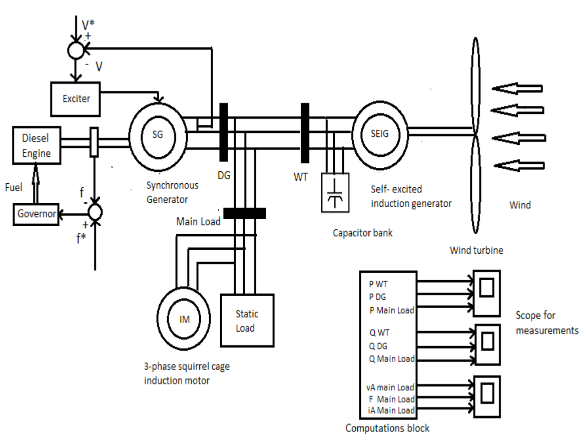


Figure 1. Modified schematic diagram of IW-D Hybrid System feeding static load and heavy load.

2.4 Modeling of Heavy Load

The modeling of heavy load in d-q axis stationary reference frame is expressed as[18]:

$$[v_m]=[R_m][I_m]+[L_m]p[I_m]+w_m[G_m][I_m] \tag{3}$$

The current obtained using equation (3) can be expressed as:

$$[I_m]=[L_m]^{-1}\{[v_m]-[R_m]-w_m[G_m][I_m]\} \tag{4}$$

Where $[v_m]$, $[I_m]$, $[R_m]$, $[L_m]$, and $[G_m]$ are defined in the Appendix.

The phase currents (i_{pa}, i_{pb}, i_{pc}) of the motor are obtained by 2-ϕ to 3-ϕ transformation and subsequently, the line currents are given as:

$$i_{am} = i_{pa} - i_{pc},\ i_{bm} = i_{pb} - i_{pa},\ \text{and}\ i_{cm} = i_{pc} - i_{pb} \tag{5}$$

The electromagnetic torque developed by heavy load is given by:

$$T_{em}=\frac{3}{4}P_m L_m(i_{sqm}i_{rdm}-i_{sdm}i_{rqm}) \tag{6}$$

The load torque (T_{ld}) is given by:

$$T_{ld}=T_{em}+\left(\frac{2J_m}{P_m}\right)\frac{dw_m}{dt} \tag{7}$$

The speed derivative of heavy load is expressed as:

$$\frac{dw_m}{dt}=\left(\frac{P_m}{2J_m}\right)T_{ld}-T_{em} \tag{8}$$

Where the heavy load have

Number of poles	=	P_m
Speed of motor	=	w_m in rpm
Moment of inertia	=	J_m in kg per m^2

2.5 Modeling of Dummy Load

The dummy load comprised of eight sets of 3-ϕ resistors connected in series with GTO thyristor switches. The rated power of each set of resistors follows a binary progression which provides the access to vary the easily in steps[9].

The power consumption of dummy load can be given as:

$$D_{STEP}.T_{ref}=\sum_{j=0}^{7}k_j 2^j.D_{STEP} \tag{9}$$

where D_{STEP} is the power corresponding to lower significant bit. The load can be varied from 0 to 204 kW in steps of 0.8 kW (T_{ref} = 0 to 204 kW and D_{STEP} = 0.8 kW). The value of k_j is '0' when the associated GTO is turned off and '1' when the associated GTO is turned on.

3. System Description and Validation

The modified schematic diagram of IW-D Hybrid System feeding static load and heavy load[16] is shown in Figure 1. It consists of a 480 V, 275 kVA SEIG driven by prime mover i.e. wind turbine. The excitation to SEIG is provided by a 75 kVAR capacitor bank by connecting in parallel with the SEIG stator terminal. The system shown is also comprised of a 400 kW diesel genset[16] which is used for maintaining the balance of power supply. The hyrid power system feeds a heavy load of 150 hp along with the static load of 200 kW.

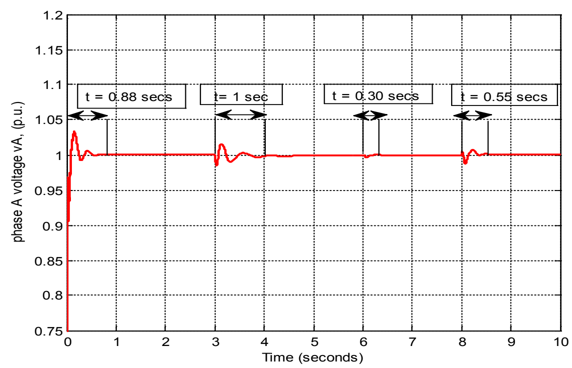
The IW-D hybrid power system feeding heavy load under various loading conditions is analyzed through modeling and simulation in MATLAB/Simulink environment[27].

Initially the diesel genset is running. The SEIG driven by wind turbine is switched on at t = 0 s. The two generating sources is feeding static load (200 kW) and heavy load runs at no-load at t = 0s, 125% of rated load at t = 3 s, rated load at t = 6 s and no-load at t = 8 s. Figure 2 shows the phase A voltage (v_A) and current (i_A) at main load terminal (consisting of both the static load and heavy load). At t = 0 s, the Hybrid System feeds the static load (200 kW) which remains same throughout the simulation and heavy load runs at no load. At this moment, the SEIG driven by wind turbine generates 206 kW but due to losses it produces 200 kW and diesel genset does not contribute any power shown in Figure 3, thus maintaining the voltage at unity after 0.88 s of starting, the value of current is less than 1 p.u. The total real power is absorbed by the main load shown in Figure 3.

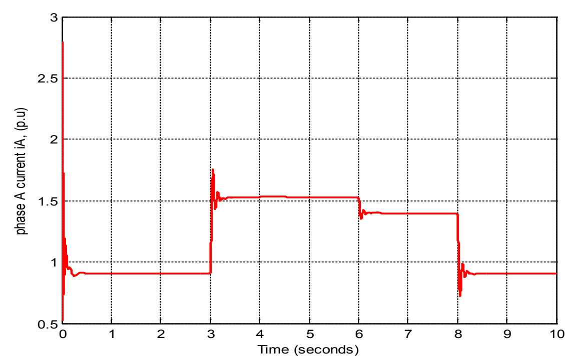
At t = 3 s, the load on heavy load is increased to 125% of the rated load. Now the SEIG produces its nominal power and the diesel genset contributes by generating power to meet increased load demand as shown in Figure 3, thus, stabilizing the system after 1 s as shown in the Figure 2. The total real power generated from WD system is shown across the main load in Figure 3. The phase A current at main load terminal is increased to 1.7 p.u.

At t = 6 s, the load on the heavy load is decreased to its rated value and again diesel genset generates the power and maintain the system stability after 0.30 s. The phase A current at main load terminal is reduced to 1.4 p.u. shown in Figure 2. At t = 8 s, the load is reduced to zero on heavy load i.e. no-load, the SEIG produces nominal power which is sufficient to meet the load demand, the diesel genset produces no real power as shown in Figure 3. The system becomes stable after 0.55 s and the phase A current across main load is reduced to less than 1 p.u. as shown in Figure 2.

As the power generated by SEIG driven by wind turbine and diesel genset is equal to the power (real) absorbed by the load, it proves the validity of the model and also the system is validated by comparing the characteristics with base paper[16].



(a)



(b)

Figure 2. (a) Voltage of phase 'A' (v_A) at main load terminal and (b) Current of phase 'A' (i_A) at main load terminal.

4. Results and Discussions

The performance of IW-D system feeding heavy load is analyzed in this section. The effect of normal load and overload on the heavy load is critically analyzed. The effect of operating conditions like frequency runaway and varying speed on the entire system and heavy load and the remedies are implemented to overcome such problems.

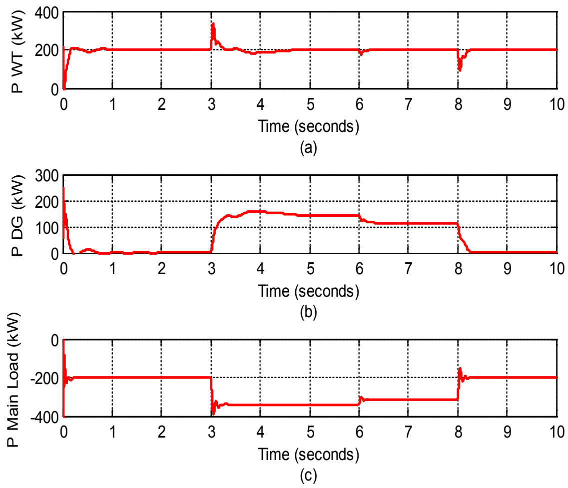


Figure 3. Real power at (a) wind turbine terminal, (b) diesel genset terminal and (c) main load terminal.

4.1 Impact on Heavy Load

The impact of various loading condition on heavy load is taken into account. The static load (200 kW) along with heavy load is being fed from W-D generation. The heavy load runs at no load, rated load and overload which is 125% of rated load[18].

Figure 4 shows the 1. Stator current of phase a (i_{spa}), 2. Rotor current of phase a (i_{rpa}), 3. Speed (w_m) and 4. Electromagnetic torque (T_{em}) of heavy load. At t = 0 s, the stator current and rotor current of phase a heavy load during no load is shown in Figure 4(a) and (b). The stator current during this period is 0.5 p.u. And the rotor current is zero. The speed is 1 p.u. and the electromagnetic torque is zero as shown in Figure 4(c) and (d).

At t = 3 s, heavy load runs at 125% of rated load thus, the stator current and rotor current of phase a heavy load is increased to 1.5 p.u. shown in Figure 4. The speed of heavy load gets reduced and the electromagnetic torque is increased as shown in Figure 4

At t = 6 s, the heavy load is made to run at rated load. The stator and rotor currents get reduced, the speed of the heavy load is increased to 1 p.u. and the electromagnetic torque is reduced to 1 p.u. shown in Figure 4. Further, at t = 8 s the load is decreased to no-load and the impact on the characteristics is shown in Figure 4.

The speed and torque characteristics of the heavy load under above conditions are shown in Figure 5.

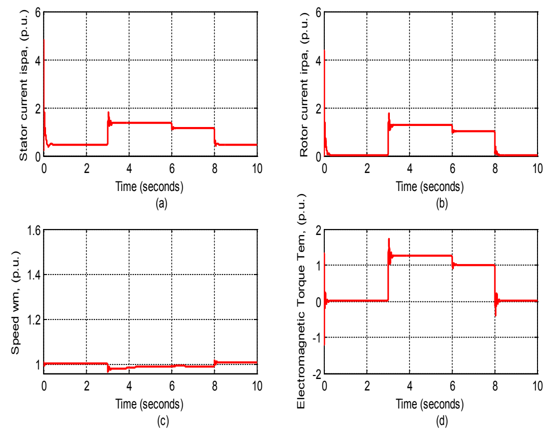


Figure 4. (a) Stator current of phase 'a' (i_{spa}), (b) Rotor current of phase 'a' (i_{rpa}), (c) Speed (w_m) and (d) Electromagnetic torque (T_{em}) of heavy load.

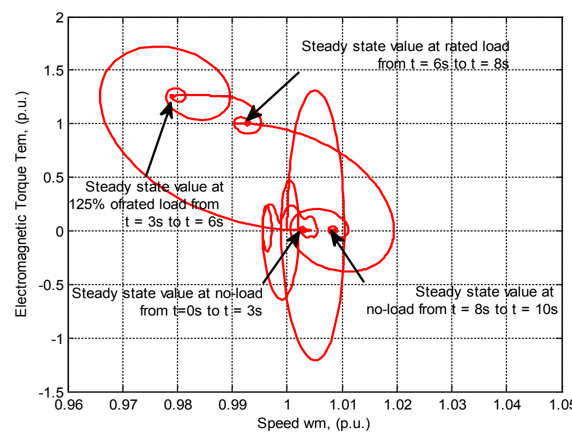


Figure 5. Speed (w_m) vs. electromagnetic torque (T_{em}) characteristics of heavy load.

4.2 Frequency Runaway

Frequency runaway is the problem which occurs when the load fed by wind-diesel system is decreased. This results in over sizing of wind turbine with respect to the load, thus the diesel governor loses its speed control and synchronous generator behaves as a motor by absorbing the real power[16].

This problem is corrected by connecting the dummy load across load terminal of 0-204 kW shown in Figure 6. The modeling of dummy load is mentioned in mathematical modeling section.

Figures 7-12 illustrates the behavior of the IW-D system without and with dummy load. The operation of the system remains the same as explained in system description and validation section but at t = 8 s, the heavy load runs at half load rather than no-load. The static load of 200 kW is removed at t = 10 s when heavy load is running at half load. At this instant, the rotor speed of the SEIG will shoot to a very high value resulting in over sizing of wind turbine but when dummy load is connected, the speed of SEIG is maintained at unity as shown in Figure 7. The frequency of the synchronous generator of diesel genset without dummy load increases but with the dummy load, it remains at nominal value i.e. 60 Hz as shown in Figure 8. The instantaneous voltage (v_A) and current of phase A (i_A) at main load terminal is shown in Figure 9. The voltage remains constant whereas the current decreases without dummy load. The current of phase A attains the value near unity with the switching of dummy load as shown in Figure 9(c) and (d).

Figure 10 shows the real power at wind turbine, diesel genset and main load terminal. At the instant of load removal the SEIG driven by wind turbine tries to generate nominal power but the load available is less, thus it provides only 100 kW and becomes oversized in comparison to load as shown in Figure 10 and the diesel genset absorbs the real power as shown in Figure 10(b) thus turns into motor. With switching on the dummy load at the same instant the excess power is absorbed by the dummy load and the diesel genset behaves as generator as shown by red line Figure 10.

The stator current (i_{spa}) and rotor current (i_{rpa}) and electromagnetic torque (T_{em}) of heavy load does not vary much due to frequency runaway and remain the same as in the normal operation but the speed (w_m) of heavy load shoots to a high value when this condition occurs. With application of dummy load, the speed attains the value of 1 p.u as shown in Figure 11. The speed and torque characteristics of heavy are shown in Figure 12.

4.3 Pitch Angle Control including Pitch Servo

Speed of wind never remains constant. It keeps on changing every time depending upon the atmospheric pressure. The pitch angle of blades is zero when there is no change in the wind speed (10 m/s). When the speed of the wind is increased the wind turbine generates more power compared to the nominal power. Thus in order to limit the power generation by SEIG driven by wind turbine to nominal value, pitch angle is controlled with the help of PI controller including pitch servo which takes input power from SEIG driven by wind turbine and nominal power therefore, processing the error with PI controller and increase the pitch angle to limit the output power (P WT) to rated value as shown in Figure 13.

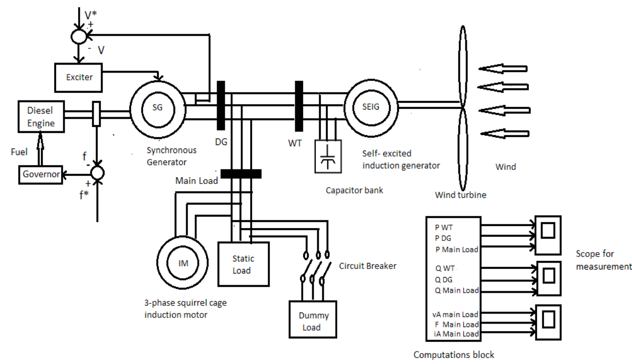


Figure 6. Modified schematic diagram of IW-D Hybrid System feeding static load, heavy load along with dummy load.

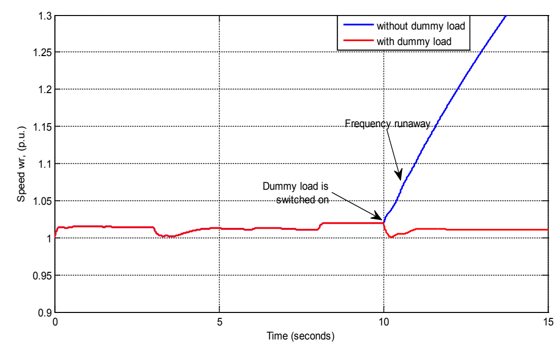


Figure 7. Speed of SEIG (w_r) driven by wind turbine without and with dummy load.

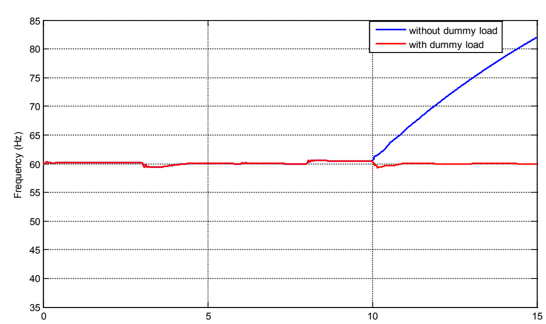


Figure 8. Frequency of synchronous generator of diesel genset without and with dummy load.

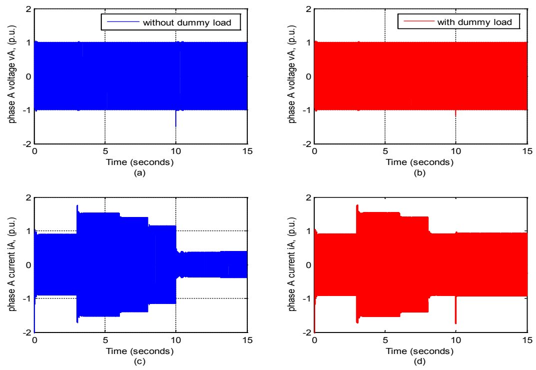


Figure 9. Instantaneous voltage of phase A (v_A) at main load terminal. (a) Without dummy load, (b) With dummy load and instantaneous current of phase A (i_A) at main load terminal, (c) without dummy load and (d) with dummy load.

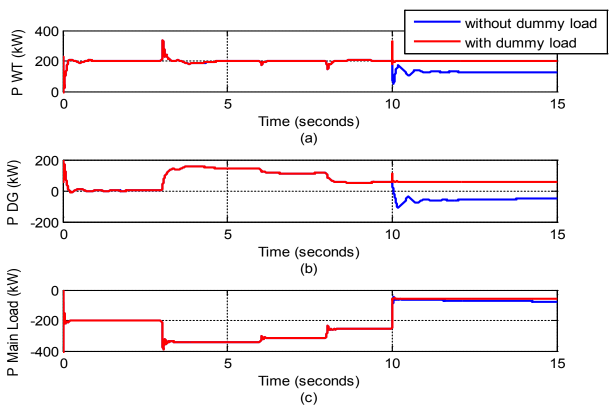


Figure 10. Real power at (a) wind turbine terminal, (b) diesel genset terminal and (c) main load terminal without and with dummy load.

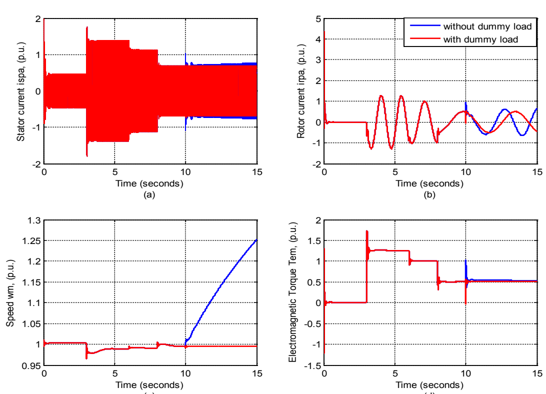


Figure 11. (a) Instantaneous stator current of phase 'a' (i_{spa}), (b) Instantaneous rotor current of phase 'a' (i_{rpa}), (c) Speed (w_m) and (d) Electromagnetic torque (T_{em}) of heavy load without and with dummy load.

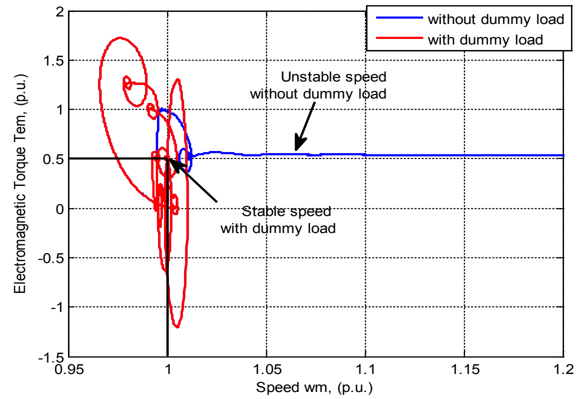


Figure 12. Speed (w_m) vs. electromagnetic torque (T_{em}) characteristics of heavy load.

The value of k_p is taken 5 and that of k_i is 25 of PI controller. Pitch servo is a non-linear device which rotates almost all the blades of wind turbine along the longitudinal axis. As shown in Figure 13 the pitch servo consists of an integrator with the time constant in a closed loop.

The modeling of pitch servo is given by:

$$\frac{d\beta}{dt} = \frac{1}{\tau}(\beta_{ref} - \beta) \tag{10}$$

Which subjects to:

$$\beta_{\min} \le \beta \le \beta_{\max}$$

$$\frac{d\beta_{\min}}{dt} \le \frac{d\beta}{dt} \le \frac{d\beta_{\max}}{dt}$$

Where

βmin and βmax are minimum pitch angle and maximum pitch angle

The response of PI controller depends upon the pitch servo time constant which lies in the range of 0.2-2.4 s. The pitch angle β ranges from 0 to 45° which varies at the rate of ± 2°/s. The rate of change of pitch angle of blades affects the performance power regulation of SEIG. The response of pitch servo is represented by rate limiter and because the pitch rate is faster the dynamic performance of PI controller is better.

The behavior of the system without and with pitch angle control is described. During the simulation, the heavy load runs at no load. With the incorporation of PI controller, the pitch angle increases from 0 to 2.20 degrees when the wind speed increases from the nominal value i.e. 10 m/s to 11 m/s at t = 5 s as shown in the Figure 14.

The real power generated by the SEIG increases to around 240 kW without PI controller but with PI controller, it attains the nominal value i.e. 200 kW in 1.3 s as shown in the Figure 15(a). At the same instant, the diesel genset absorb the real power without PI controller and behaves as a motor but with the PI controller it absorbs zero real power and behaves normally after 1.4 s as illustrated in Figure 15. The total real power is fed to the main load shown in Figure 15

The voltage (v_A) and current (i_A) of phase A at main load terminal remains almost same due to smooth pitch angle control as illustrated in Figure 16.

The stator current (i_{spa}) and rotor current (i_{rpa}) of heavy load does not vary much with and without PI controller. The speed (w_m) is increased at t = 5 s without PI controller. But it remains constant with the implementation of PI controller. The electromagnetic torque (T_{em}) almost remains constant shown in Figure 17.

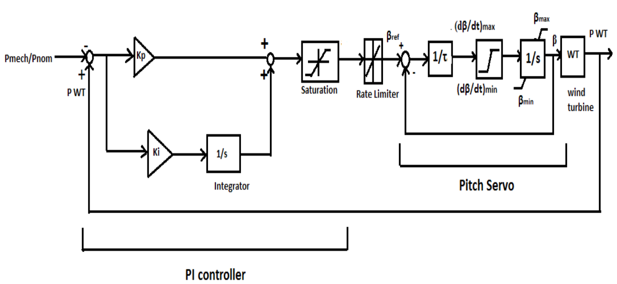


Figure 13. Block diagram of pitch angle control incorporating PI controller with pitch servo.

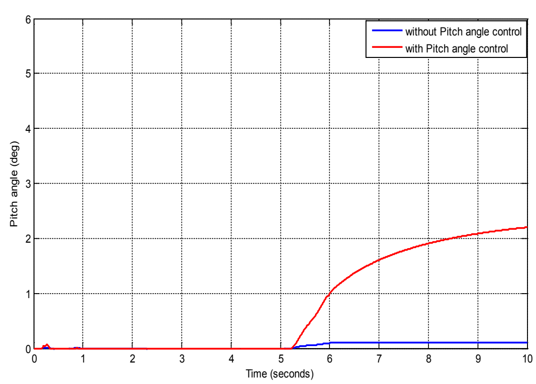


Figure 14. Pitch angle of wind turbine under varying wind speed without and with pitch angle control.

Figure 18 shows the speed torque characteristics of heavy load in which blue line indicates that with the increase in the speed of wind, the speed of heavy load also increases and reaches a high whereas the torque does not vary much which results in electrical and mechanical damage to the heavy load but with the help of PI controller and pitch servo, the output of SEIG is maintained to its nominal value much faster and it ensures proper functioning to the heavy load without any damage and fatigue.

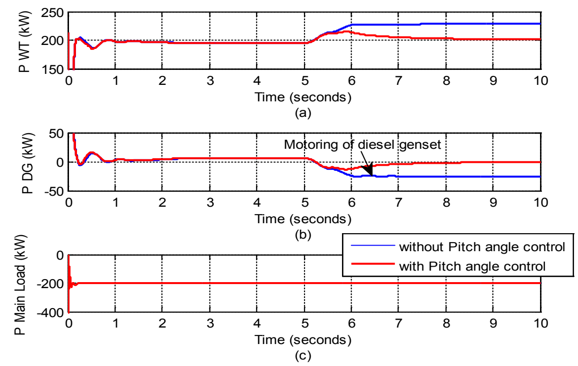


Figure 15. Real power at (a) Wind turbine terminal, (b) Diesel genset terminal and (c) Main load terminal without and with pitch angle control.

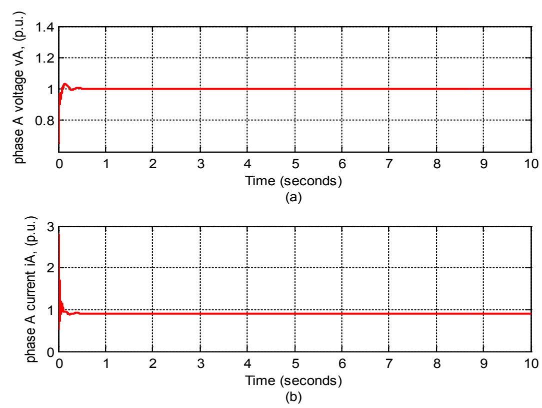


Figure 16. (a) Voltage of phase 'A' (v_A) at main load terminal and (b) Current of phase 'A' (i_A) at main load terminal without and with PI controller.

5. Conclusions

The IW-D Hybrid System feeding heavy load under various loading conditions has been validated. The impact on the heavy load being fed from two sources has been analyzed. The main focus of the work is to overcome the shortcomings like frequency runaway and controlling pitch angle of wind turbine in case of increasing wind speed due to which diesel genset absorbs real power and behaves as a motor.

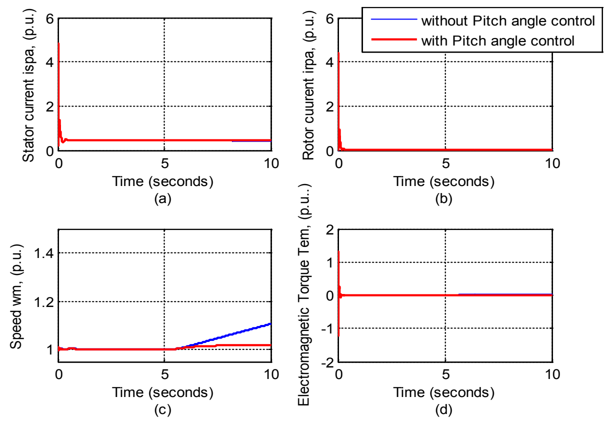


Figure 17. (a) Stator current of phase 'a' (i_{spa}), (b) Rotor current of phase 'a' (i_{rpa}), (c) Speed (w_m) and (d) Electromagnetic torque (T_{em}) of heavy load without and with pitch angle control.

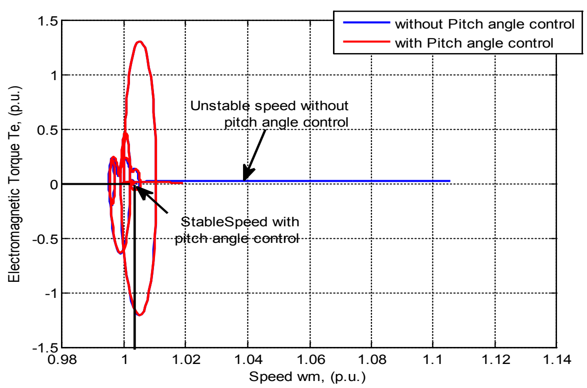


Figure 18. Speed (w_m) vs. electromagnetic torque (T_{em}) characteristics of heavy load without and with pitch angle control.

Technical solutions have been provided like dummy load is connected across the main load which absorbs excess power when load is reduced to overcome frequency runaway problem.

Another solution for pitch angle control is provided with the help of PI controller including pitch servo to limit the power produced by SEIG driven by wind turbine to nominal value when the speed of wind increases the base value (10 m/s).

Thus in both the solutions diesel genset is prevented from turning into motor and major chunk of energy is harnessed from wind generation ultimately saving fuel consumption and promoting more use of pollution free energy.

At last, the effect of frequency runaway and the varying wind speed on the heavy load has been analyzed to check the robustness of the system.

6. Appendix

Parameters of SEIG: 275 KVA, 480 V, 60 Hz, two- pole pairs having:

Stator resistance:	R_{sg}	=	0.016 p.u.
Rotor resistance:	R_{rg}	=	0.015 p.u.
Stator inductance:	L_{sg}	=	0.06 p.u.
Rotor inductance:	L_{rg}	=	0.06 p.u.
Magnetizing inductance:	L_{mg}	=	3.5 p.u.
Inertia constant:	H_g	=	2 secs

Parameters of heavy load: 150 hp, 460V, 60 Hz, 1785 rpm, two-pole pairs having:

Stator resistance:	R_{sm}	=	0.01597 p.u.
Rotor resistance:	R_{rm}	=	0.009103 p.u.
Stator inductance:	L_{sm}	=	0.05642 p.u.
Rotor inductance:	L_{rm}	=	0.05642 p.u.
Magnetizing inductance:	L_{mm}	=	1.354 p.u.
Inertia constant:	H_m	=	2 secs

Model matrices of heavy load: Matrices of Equation (3) are defined as:

$$[v_m] = [v_{sdm}, v_{sqm}, v_{rdm}, v_{rqm}]^T$$

$$[i_m] = [\, i_{sdm}, i_{sqm}, i_{rdm}, i_{rqm}]^T$$

$$[R_m] = \mathrm{diag}\,[R_{sm}, R_{sm}, R_{sm}, R_{sm}]$$

$$[L_m] = \begin{bmatrix} L_{sm}+L_{mm} & 0 & L_{mm} & 0 \\ 0 & L_{sm}+L_{mm} & 0 & L_{mm} \\ L_{mm} & 0 & L_{rm}+L_{mm} & 0 \\ 0 & L_{mm} & 0 & L_{rm}+L_{mm} \end{bmatrix}$$

$$[G_m] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_{mm} & 0 & L_{rm}+L_{mm} \\ L_{mm} & 0 & L_{rm}+L_{mm} & 0 \end{bmatrix}$$

Subscript:

A	=	Phase A of main load.
a	=	Phase A of heavy load.
q	=	Quadrature axis.

d	=	Direct axis.
s	=	Stator quantities.
r	=	Rotor quantities.
g	=	Generator quantities.
m	=	Heavy load quantities.
k	=	Binary number.
WT	=	Wind turbine.
DG	=	Diesel genset.
G_m	=	Conductance of heavy load.

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