Performance and Investigation of Two Drive Train Interfaced Permanent Magnet Synchronous Generator for Wind Energy Conversion System

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Abstract: Wind energy conversion system in electricity power production has increased rapidly owing to enormous technical developments significantly reducing cost leading to economic production of energy. The use of conventional way generating resources have been made since many decades. Though each one of us has received the useful amount of energy from these resources yet comes with the price. Most of these are extracted from the fossil fuel and it is pretty clear that these are not at all eco-friendly. Moreover as time has passed the availability of these resources is not decreasing. Which tends to reflect the effect in the rise of their prices. Hence, the intellectual individuals in the field of energy generation are inclining more towards the renewable resources as these are renewable. The work presented in this has its focal point on wind energy. It is very unpredictable but has quite potential to participate in fulfilling the energy demand in current scenario. The energy generation is done via PMSG which requires a suitable technique for controlling it in extracting maximum power. Due to the random and unpredictable nature of wind, it is difficult to get the maximum output from it and hence require maximum power point tracking (MPPT) controller. This thesis focuses on the development of two drive train interfaced Permanent magnet synchronous generator (PMSG) for wind energy conversion system (WECS). It focuses on design and modeling aspects of the different components of the WECS like the basic model of two drive train, converters, wind turbine, optimal maximum power point tracking system using MATLAB/Simulink. The thesis displays the model of wind turbine along with the model of PMSG. The MPPT technique used here is based on Perturbation and observation (P&O). To complete the process of modeling and simulation the platform of MATLAB/Simulink is utilized. This ensures the MPPT. As the wind speed is random and vary all the time, effective generation losses occurs due to the disturbance in system voltage frequency. To counter it voltage source converter (VSC) is in operation with voltage & frequency controller. The analysis is carried out for different wind speed profile. WECS laboratory prototype is used and experimental results are developed for it. It shows the improvements for the system and control action for balance/unbalanced steady state as well as dynamic conditions.

Keywords: *Maximum Power Point Tracking, MPPT Algorithm, WECS.*

I. INTRODUCTION

The depletion in the reserves of fossil fuels considered as traditional sources of power generation at an alarming rate coupled with the level of environmental pollution associated with them have shifted the focus towards harvesting non-conventional energy sources such as wind and solar energy for power generation. Wind energy is environment friendly and the cleanest source of energy. The foremost benefits of wind energy are wind-generated electrical energy does not cause air or soil & water pollution. Among many countries India is one which has the highest generation of power from nonconventional resources. In the power market, nonconventional power contribution is approx. 34.4% of the gross power generated. Nearly 73.36 Gigawatt of total nonconventional power capability have been put within India as on Oct. 2018 out of all nonconventional power resources that incorporate approx. 34.97 Gigawatt by wind, 24.34 Gigawatt by solar, 4.5 Gigawatt by little hydro power & 9.55 Gigawatt by bio power. In addition 46.74 Gigawatt capabilities are in progress. The authority has acknowledged the mechanical phenomenon of installing sixty Gigawatt capability of solar energy & twenty Gigawatt capability of wind power until year 2020. As on March 31, 2018 wind power capacity was 34,046 MW. India is at fifth place for overall put in renewable energy capability fourth place for wind energy and fifth place for solar energy. Total power output of wind energy conversion system depends mainly on precision due to which maximum power point is tracked using the MPPT controller of the wind energy conversion system which doesn't depend on the type of generator used. The peak power extraction algorithm which was invented can be classified into 3 important control mechanisms: (i) Tip Speed Ratio Control (TSR) (ii) Power Signal Feedback Control (PSF) & (iii) Hill-Climb Search Control (HCS) or perturbation and observation (P&O).

II. MATERIALS AND METHODS

A. Wind turbine dynamic model

It gives control principles & modeling of wind turbine i.e
Characteristics of wind turbine. Wind power (P_{wind}) is obtained from the wind is given as:

$$P_{wind} = \frac{1}{2}\rho A v^3 C_p(\lambda,\theta) \tag{1}$$

Here ρ = air density in kg/m^3

A = cross sectional area of the rotor blades in m^2

V = wind speed in m/s.

C_p= Rotor efficiency or power coefficient and it is the function of tip speed ratio (TSR) and pitch angle (θ).

Peak rotor efficiency C_p is realized at a specific value of TSR, This depends upon aerodynamic design of the turbine. To keep TSR fixed at the particular level all the time the rotor must move at high speed for high wind and at low speed for less wind. Wind turbines having high tip speed ratios are chosen for function over a large span of wind speeds.

A group of C_p – curves including pitch angle as the main consideration, achieved by computation or measurement may be presented as a nonlinear function.

The function is as follows.

$$C_p = C_1(C_2 - C_3\theta - C_4)\exp(-C_5) \tag{2}$$

Here θ = Pitch angle.

If coefficients $C_1 - C_5$ are properly adjusted then better simulation results are obtained for given turbine.

Purpose of PMSG to transform the mechanical power of turbine into electrical power, it is more preferred for this purpose, because of its more favorable properties such as absence of gearbox, high power density, small size, reduced weight and external excitation.

This dynamic model considers a back e.m.f. of sinusoidal nature, no saturation, and minor iron losses. It assumes the iron (hysteresis & eddy current) losses and the dynamic equations of permanent magnet synchronous generator (PMSG) currents are:

$$\frac{di_{md}}{dt} = \frac{1}{L_d}(v_d - R_{st}i_d + \omega L_q i_{mq}), \tag{3}$$

$$\frac{di_{mq}}{dt} = \frac{1}{L_d}(v_q - R_{st}i_q + \omega L_q i_{md} - \omega\psi_{PM}), \qquad i_d = \frac{1}{R_c}\left(L_d\frac{di_{md}}{dt} - \omega L_q i_{mq} + R_c i_{md}\right),$$

$$i_q = \frac{1}{R_c}\left(L_q\frac{di_{mq}}{dt} + \omega L_d i_{md} + \omega\psi_{PM} + R_c i_{mq}\right),$$

$$i_{cd} = i_d - i_{md},$$

$$i_{cq} = i_q - i_{mq}, \tag{4}$$

here i_q& i_d, are d_q axes currents, V_q&V_d, are the d_q axes voltages, i_{cd}' i_{cq} are the d_q axes iron losses currents, i_{md}, i_{mq} are the d_q axes magnetizing currents, L_d, L_q are the d_q axis inductances, If$\Psi_{pm}$is the mutual flux of magnets, ω is the fundamental frequency of the stator currents, R_c is resistance of the iron losses &$R_{st}$is the resistance of stator.

The electromagnetic torque equation of permanent magnet synchronous generator is:

$$T_e = \frac{2}{3}p\left[\psi_{PM}i_{mq} + (L_d - L_q)i_{md}i_{mq}\right] \tag{5}$$

Here p = number of pole pairs

B. Two mass drive train

For generating small power there are two generators

- self-excited induction generator
- PMSG

RPM of wind turbine and rotor is low and high respectively. Gearbox gives the generator turbine required speed by converting wind turbine low speed. Gearbox is not need in multi pole machines. Two mass drive train is expressed as,

$$2H\frac{d\omega_t}{dt} = T_{m-}T_s \tag{6}$$

$$T_s = K_{ss}\theta_{sta} + D_t\frac{d\theta_{sta}}{dt} \tag{7}$$

Where is the inertia constant of the triangle, θsta is the shaft twist angle, $\omega_t$is the angular speed of the wind turbine, ω_r is the rotor speed of the generator, $\omega_{ebs}$is the electrical base speed, $T_s$is the shaft torque, is K_{ss} the Shaft stiffness, D_t is the Damping coefficients.

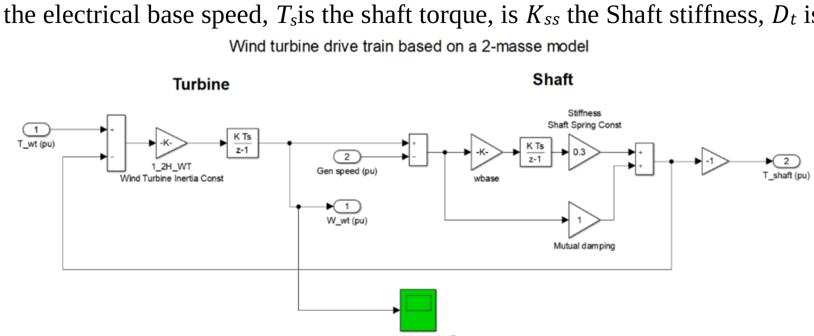


Fig. 1: Simulink model of two mass drive train for wind turbine

III. MPPT FOR WIND ENERGY CONVERSION SYSTEM

The MPPT technique is implemented to obtain the maximum power from the available wind speed. MPPT is implemented into the system to track the voltage operating close to the maximum power during varying condition. MPPT is also used for maintaining the stable voltage through operation thus making it grid capable.

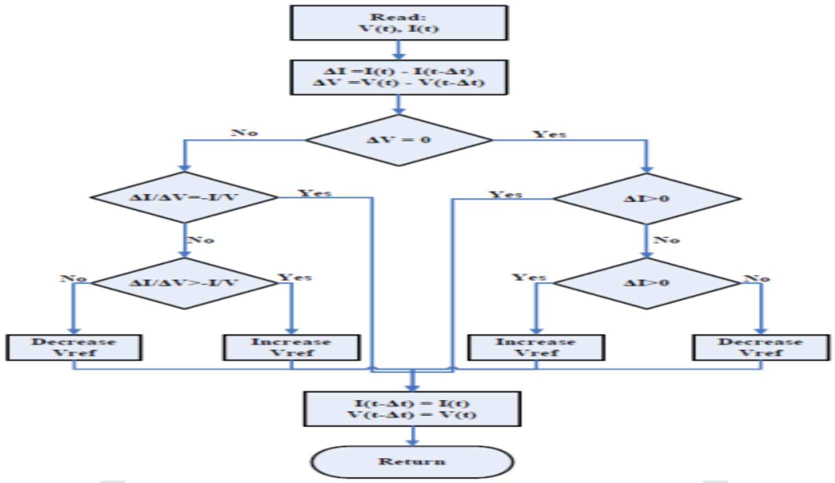


Fig 2: Flowchart of MPPT algorithm

P&O method is most common MPPT algorithm which is used extensively in small WECS. It periodically monitors and compare the output power or voltage of the system to the previous value and thus perform the perturb operation. If the difference between observed value and the previous value is positive, then the perturbation is performed in positive direction. If the variation tends to negative then the perturbation is reversed as shown in Fig.2. This process is continued until the maximum power is achieved. The oscillation in the system depends on the size of the perturbation. In this paper, variable step method is used to search the MPP where the step length is adjusted according to the distance to the MPP. The duty cycle of P&O is generated through voltage and power relationship of wind system. The main drawback of the P&O algorithm is tradeoff between the oscillation and the response around the MPP during non-linear condition. P&O fails to track the MPP when there is large and rapid variation in wind speed.

IV. RESULTS &DISCUSSIONS

A.PMSG BASED WECS WITH TWO DRIVE TRAIN SIMULATIONS

This concern with the developed Simulink model simulation. This displays the simulated results and observations obtained from the developed system in MATLAB/Simulink. First the developed wind energy generation system performance is evaluated for different input wind speed.

B.CHARACTERISTICS OF PMSG BASED WIND ENERG CONVERSIONSYSTEM MODEL

The turbine power output and turbine speed characteristics are given below figures for different input wind speed. The figures are obtained with the default parameters (base wind speed = 12 m/s, maximum power at base wind speed = 0.8 pu and base rotational speed = 1.2 pu). The wind speed is changed from 6m/s to 13.2m/s to draw a curve between turbine output power (p.u.) & speed of turbine (p.u.). The actual wind turbine speed is 12m/s or 1.2 p.u. Fig. 3 shows the turbine power characteristics at the pitch angle β=0º.Fig. 4 shows the turbine power characteristics at the pitch angle β=5º

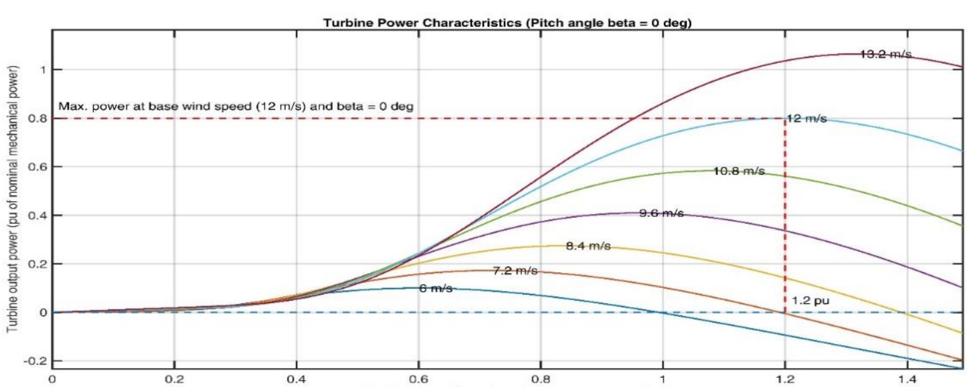


Fig. 3:Turbine power characteristics of WECS at beta 0º

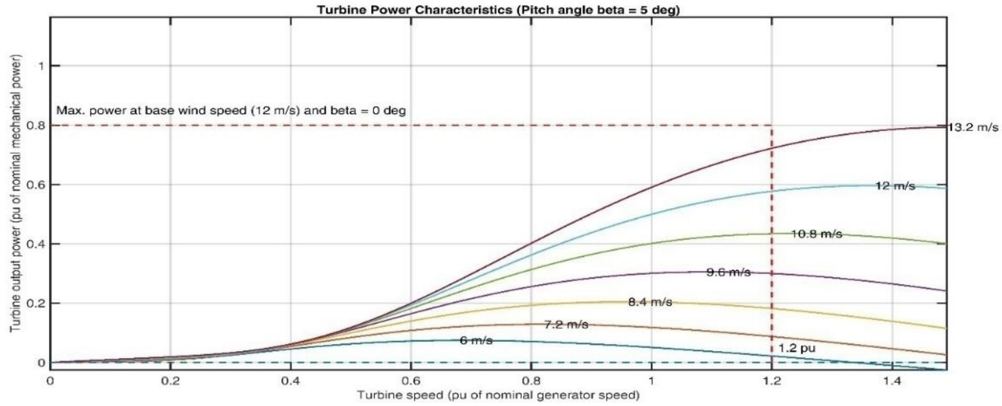
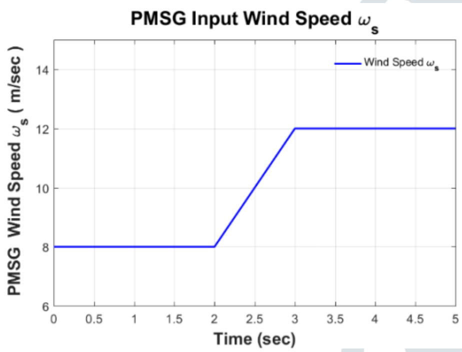


Fig. 4:Turbine power characteristics of WECS at beta 5°

Case-1 Simulation for 8 to 12 m/s(wind speed)

Signal builder block provides the mentioned input speed variation for investigating the robustness of the developed technique.



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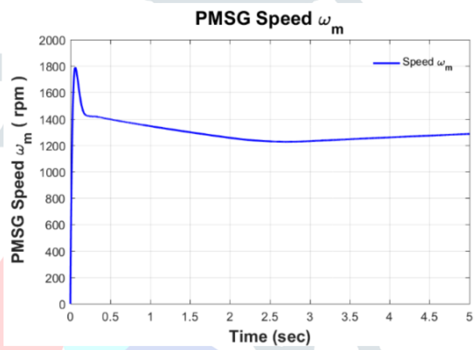

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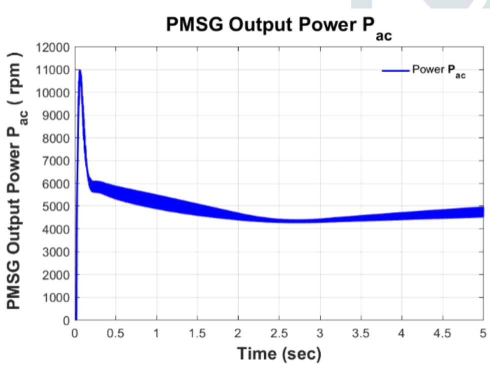

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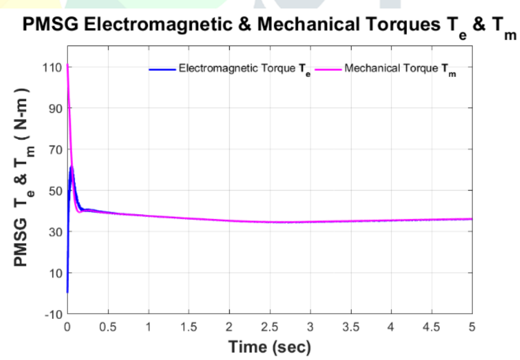

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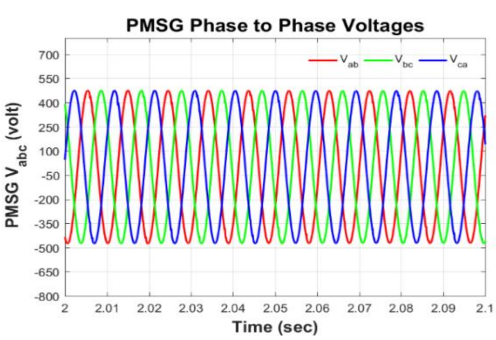

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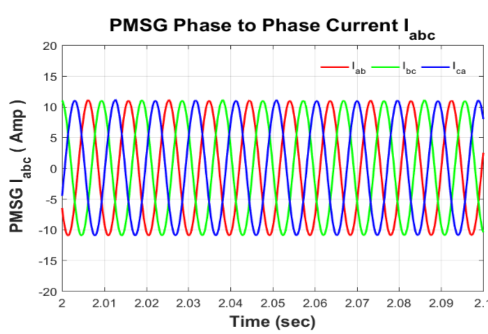
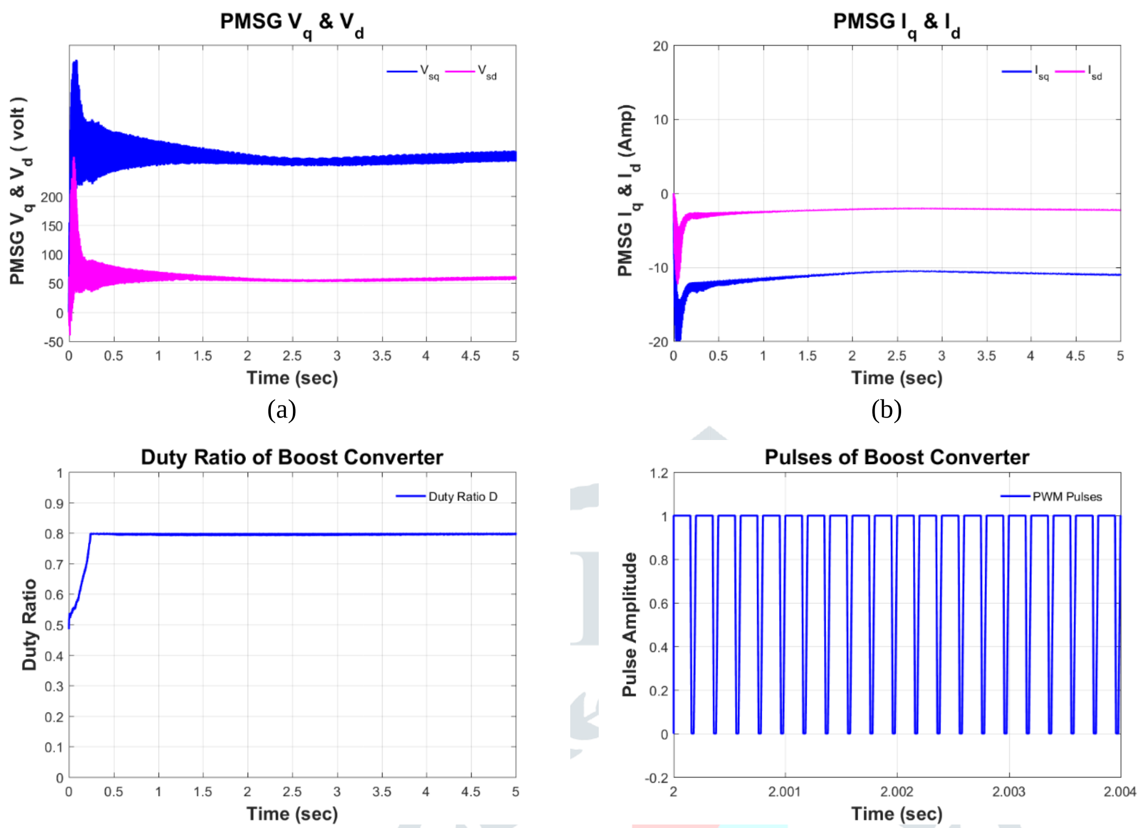


(f)

Fig. 5: Waveforms for ω_s=8to12m/s, ω_m, P_{ac}, T_e&T_m, $V_{ab}V_{bc}V_{ca}$, $I_aI_bI_c$

PMSG speed ($\omega_m \approx 1200rpm$), PMSG output power ($P_{ac} \approx 5000watt$), Electromagnetic & mechanical torque ($T_e, T_m \approx 40N-m$), PMSG phase to phase voltages ($V_{ab}, V_{bc}, V_{ca} \approx 500v$), PMSG phase current ($I_a, I_b, I_c \approx 12amp$). It can be seen that the dynamic performance given by PMSG is better here. Torque response is also improved.



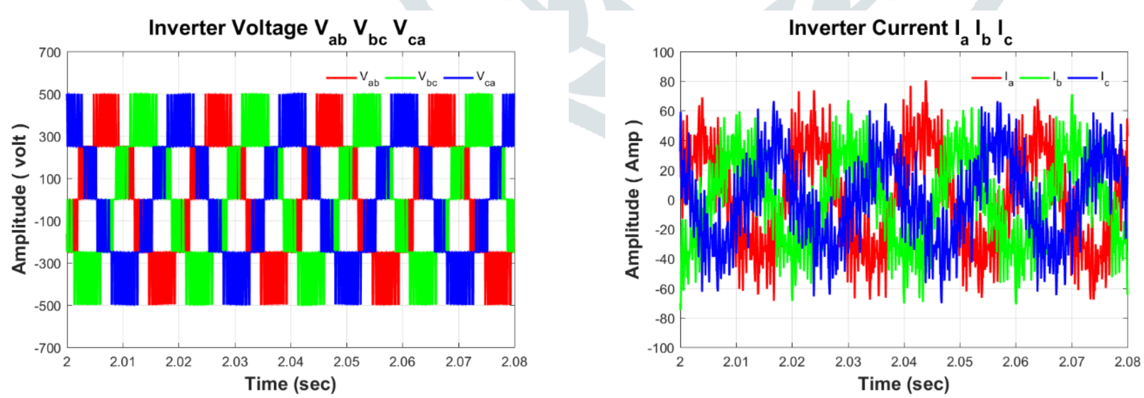
(a) (b)

(c) (d)

Fig. 6: Results for DC DC Converter(ω_s=8to12m/s),

(a) PMSG V_q & V_d (b) PMSG I_q & I_d (c) Duty ratio change, (d) DC DC converter switch's Pulses

Width of pulses varies as the duty varies. The generated PWM is 5kHz PWM. After every 2ms update in Duty ratio take place.DC link capacitor receieves output of DC-DC converter and it maintains primarily inverter input DC voltage.



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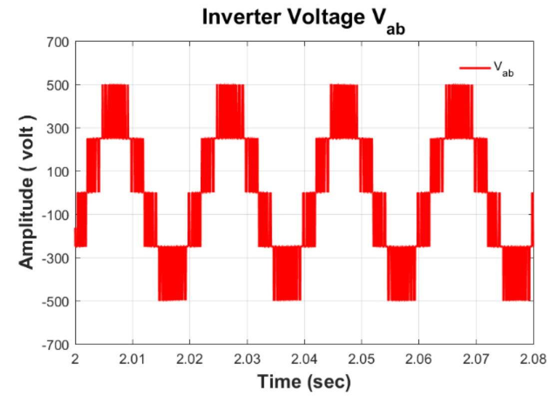

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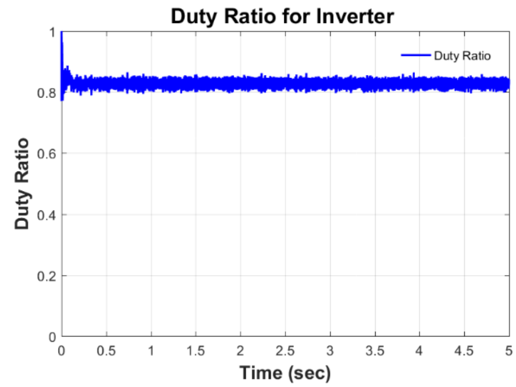

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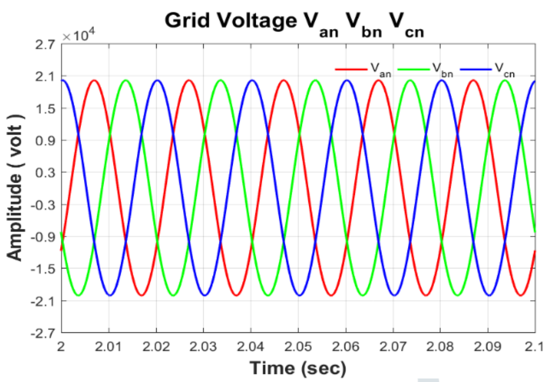

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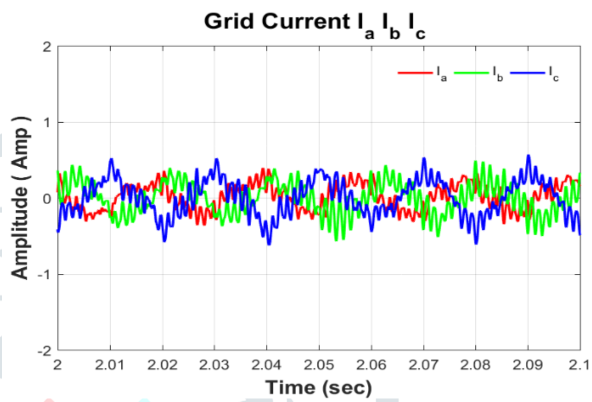

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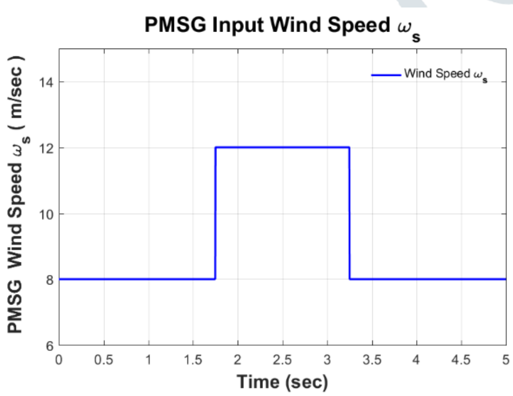
Fig. 7: Results for multilevel inverter(ω_s=8 to 12m/s), (a) $V_{ab}V_{bc}V_{ca}$, (b) $I_aI_bI_c$, (c) V_{ab}, (d) Duty ratio (e) Grid Voltage V_{an}, V_{bn}, V_{cn} (f) Grid Current I_{an}, I_{bn}, I_{cn}

Case-2 Simulation for Wind Speed of 8-12-8 m/s

Signal builder block provides the mentioned input speed variation for investigating the robustness of the developed technique.



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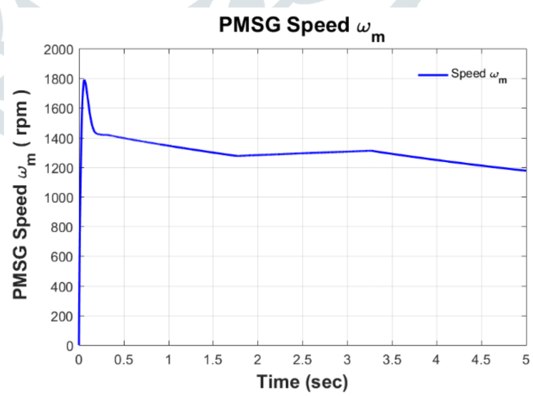

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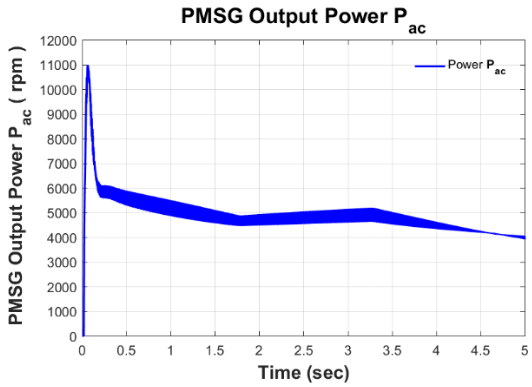

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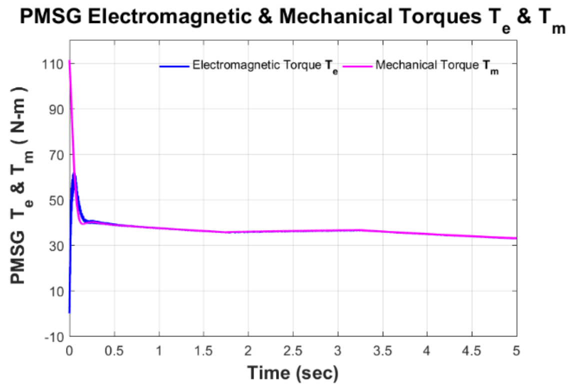

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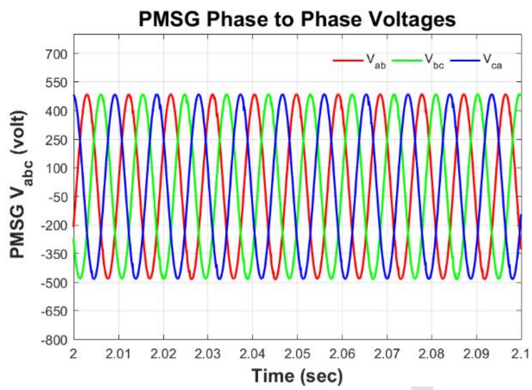

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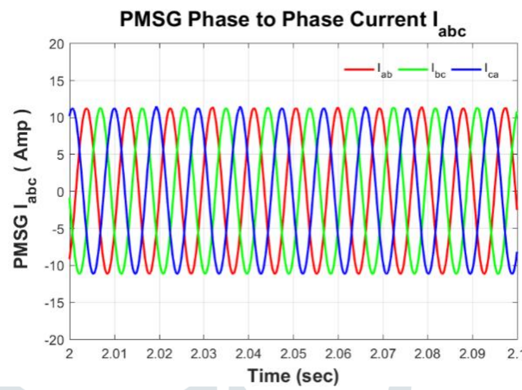
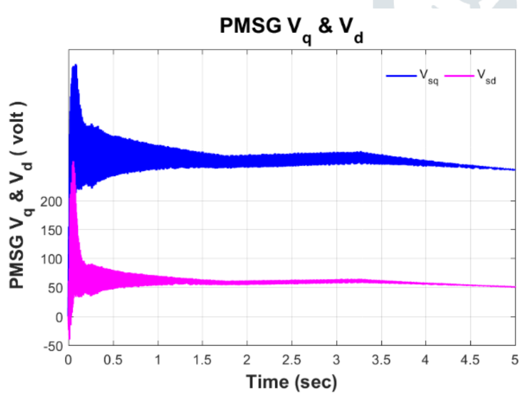


(f)

Fig. 8: Waveforms for ω_s=8-12-8m/s, ω_m, P_{ac}, T_e&T_m, $V_{ab}V_{bc}V_{ca}$, $I_aI_bI_c$

PMSG speed ($\omega_m \approx 1300rpm$), PMSG output power ($P_{ac} \approx 5000watt$), Electromagnetic & mechanical torque ($T_e, T_m \approx 35N - m$), PMSG phase to phase voltages ($V_{ab}, V_{bc}, V_{ca} \approx 500v$), PMSG phase current ($I_a, I_b, I_c \approx 12amp$). It can be seen that the dynamic performance given by PMSG is better here. Torque response is also improved.



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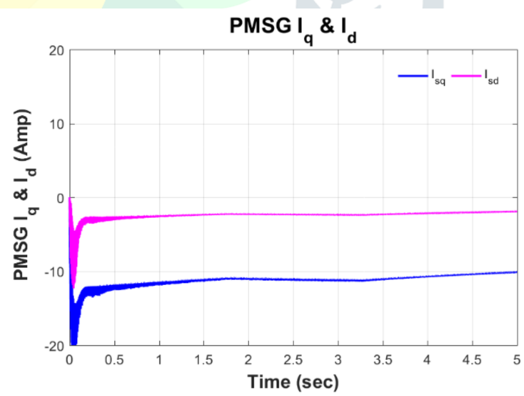

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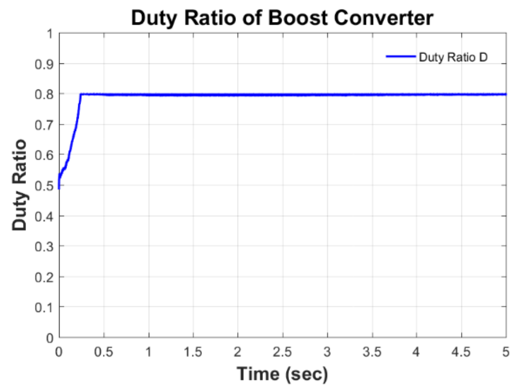
Fig. 9(a) V_qV_d (b) I_qI_d



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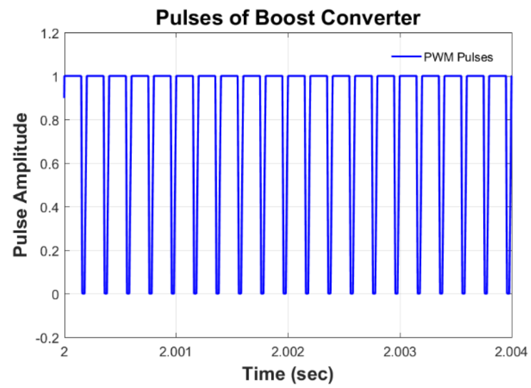


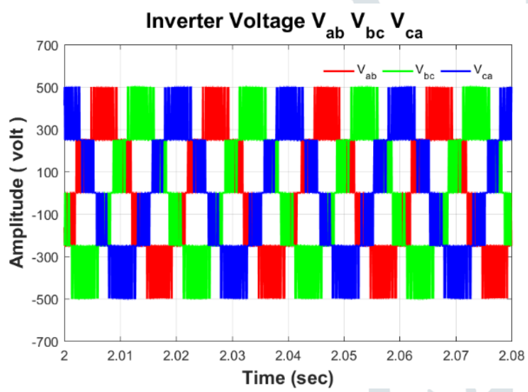
(b)

Fig. 10: Results for DC DC Converter(ωs=8-12-8m/s),

(a) PMSG V_q & V_d (b) PMSG I_q & I_d (c) Duty ratio change, (d) DC DC converter switch's Pulses

Width of pulses varies as the duty varies. The generated PWM is 5kHz PWM. After every 2ms update in Duty ratio take place.

DC link capacitor receieves output of DC-DC converter and it maintains primarily inverter input DC voltage.



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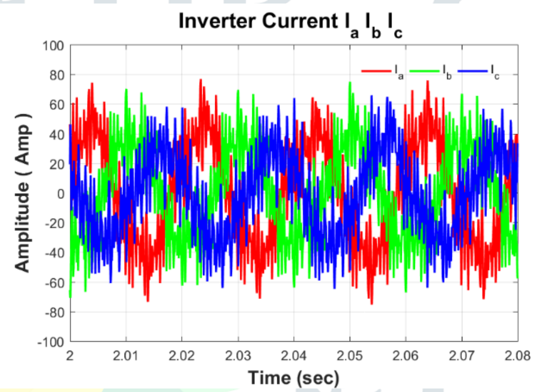

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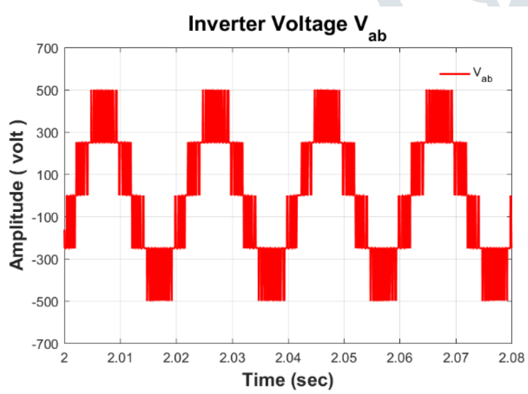

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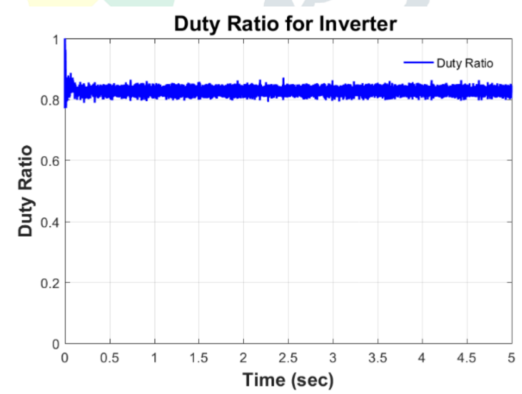


(d)

Fig. 11: Results for multilevel inverter(ωs=8-12-8m/s), (a) $V_{ab}V_{bc}V_{ca}$, (b) $I_aI_bI_c$, (c) V_{ab}, (d) Duty ratio

Grid voltage is maintaining at 20kV and 50Hz.

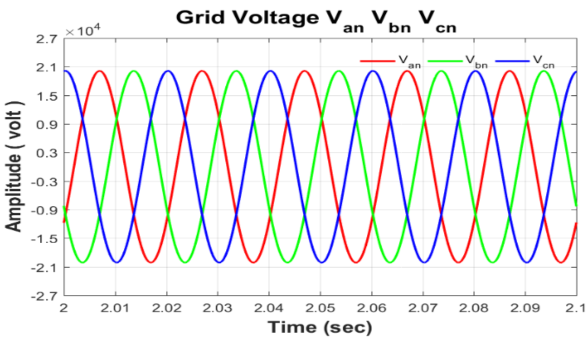


Fig. 12: Simulation results of grid side phase voltages $V_{an}V_{bn}V_{cn}$at input wind speed varying 8-12-8 m/s

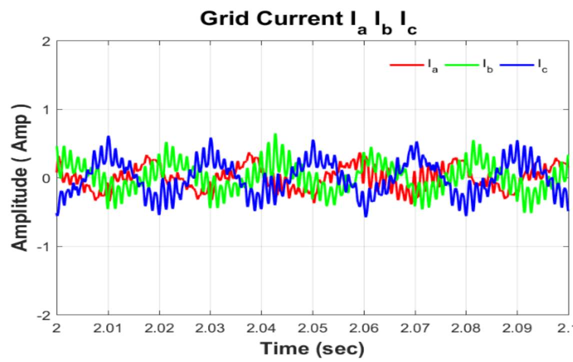


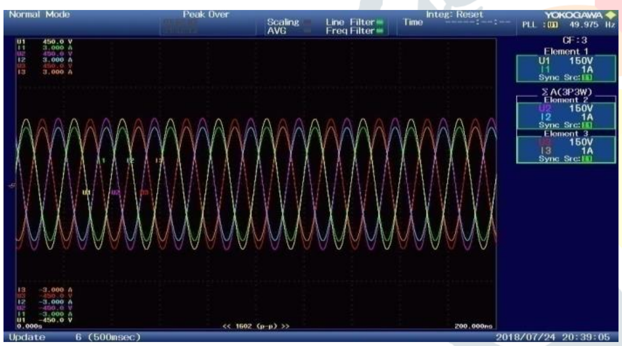
Fig. 13: Simulation results of grid side phase current $I_aI_bI_c$at input wind speed varying 8-12-8 m/s

C. **HARDWARE RESULTS OF PMSG BASED WECS WITH TWO DRIVE TRAIN**

For different conditions, the experiment is carried out for WECS lab prototype in isolated mode for its control method verification. The important task to keep its frequency and voltage at desired value. For the desired voltage at load inverter is fed with current of certain amount corresponding to rated voltage.

CASE-3: Response at Resistive(R) load with 1200 rpm

The PMGS load current & voltages good equilibrium is seen in Fig. 14. Plus these waveforms shown are balance too. The regulation of 3Φ load current and voltage is good too for operation with resistive load at unity power factor(PF). Also, these are in within safe limits.



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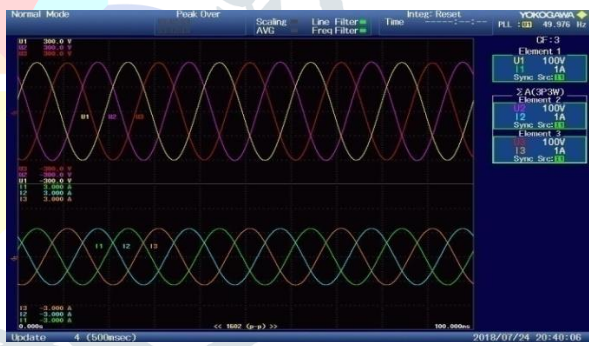

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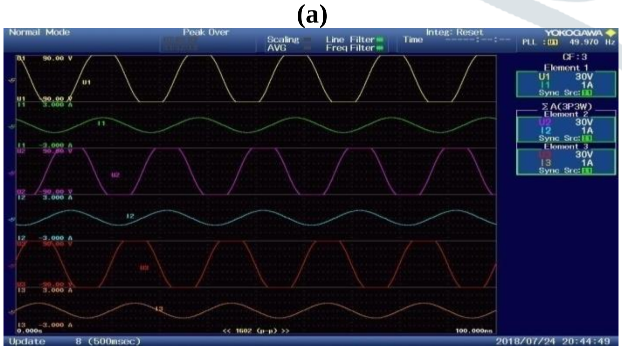

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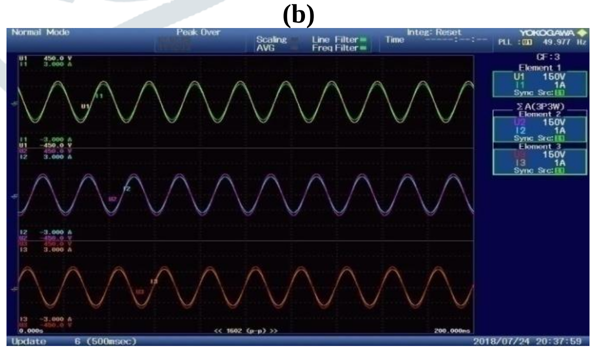

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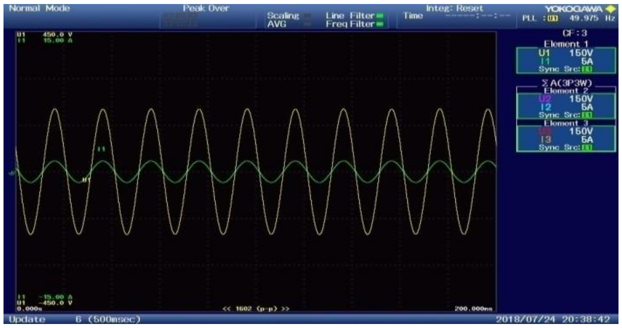

(e) **(f)**

(g)

Fig. 14: Experimental waveforms during constant resistive load of 1 kW at 1200 rpm, load waveform of (a) Three phase load voltage and current combined, (b) Three phase load voltage and current, (c) Load all Phase voltage and current, (d) Combined Load phases voltage and current , (e) Phase A Voltage and current V_aI_a , (f) load voltage and current Phasor diagram and (g) Output power waveform P, Q, S and λ

From load current harmonic spectrum of Fig.15 (a, b, c, d), it can be seen that voltage and current harmonic of converter is 5.20% and 1.20%, whereas that of load voltage and current is 0.38 % and 0.33%, which is less than 5% and it is in consent with the permissible limits of IEEE 1547, IEEE-519 and IEC 61727 standards and thus satisfies the general standards of produced power in terms of voltage and current inside 5% THD.

(a) Harmonic spectrum of output voltage of converter

(b) Harmonic spectrum of output current of converter

(c) Harmonic spectrum of output load voltage

(d) Harmonic spectrum of output load current

Fig. 15: Experimental response of harmonic spectrum of currents and voltages

The converter topologies for wind power, has obtained with low THD and the power factor is unity. This is comparatively better than 0.94% and 4.25% THD (Oliveira et al. 2015). By this generator conduction losses reduced by about 13%. It shows improvement as expected while comparing with same kind of work. So it is verified that the use of multilevel converter interfaced WECS maintains the voltage-frequency within the limits of 415 V and 50Hz. Also, it is obtained with low harmonic characteristics. For balanced regulated voltages-currents the performance of controller is very goof as verified by the results obtained. Here, low-voltage and current harmonics of 0.38% and 0.33% are as per IEEE standards.

VI. CONCLUSION AND FUTURE SCOPE

A. Conclusion

In this work, two drive train PMSG based wind energy conversion system is developed using MATLAB/simulink. Developed system associate with grid connected structure using AC-DC-AC conversion. Fuzzy logic controller have been effectively use to optimize the performance of two drive train PMSG based wind energy conversion system. Modeling and simulation of grid connected two drive train PMSG based WECS was performed in MATLAB/simulink environment. The developed overall scheme were tested with variable speed of wind. According to the simulations outcome and response pinpoint the following conclusion:

- A dynamic model of the proposed two drive train PMSG based wind wind energy conversion system has been success fully developed.
- The developed control strategy improves the output power and efficiency as compared to the conventional method.
- The simulation and experimental results represents improvement in efficiency with minimum ripple in output power.
- A good equilibrium among the load voltage and load current can be seen from simulation and experimental results. Also it can be seen from the results that total harmonic distortion of load voltage and load current is 0.38 and 0.33 respectively for resistive loads, which is less than 5% with the permissible limits of IEEE standard and satisfies the general standards of produced power in terms of voltage and current inside 5%.

B. Future Scope

In considering with literature reviewed and proposed scope of thesis works the following issues can be additionally worked to design a well-organized and almost executable wind system. The following approaches or schemes could be use as future work in the field:

- Due to high switching losses, new converter topology with lesser switches can also be implemented.
- More robust MPPT techniques based on artificial intelligent could be develop.
- There is further need in strategy for converter to reduce duty losses.
- Hydropower, biomass, geothermal energy, and other non conventional sources have to be studied; few of them are efficiently feasible for installation in remote communities for Hybrid system.

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