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Design And Investigation of Sliding Mode Control Based DC-link Converter of Hybrid Microgrid System

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Abstract

Hybrid Renewable Energy Systems (HRES) acts as optimal choice for the design of the electrical grid benefiting in social, economic and environmentally. This study interconnects wind, solar and Battery energy to transmit power to the load or grid thereby reducing the dependency on the conventional energy sources. Amidst the available non-conventional energy sources, this paper employs wind, solar and battery as the primary energy source for HRES. The suggested scheme involves wind driven permanent magnet synchronous generator, solar module, battery energy storage and necessary power converters along with suitable controllers. This investigation presents the Sliding Mode Controller (SLC) for maximum power extraction from wind and solar in order to maintain constant DC-link voltage. The generated power feeds the load through three-phase inverter. This paper compares the performance of the system using SMC and Perturb & Observe method (P&O) algorithm in Matlab/Simulink. The observed results prove the effectiveness of the SMC controller over P&O method with fast response during the change in operating condition.

1. Introduction

The rapid diminishment of Conventional Energy Sources (CES) and the stimulated demand for power places a serious challenge in meeting the power needs of the consumers [1]. Besides fast depleting nature, CES causes more degradation issues in the environment and causes ecological issues, thereby polluting the society [2]. These issues have forced the means for the progression of the most proper Non-Conventional Energy Resources (NCES) like biomass, wind, hydro, solar and geothermal, which are eco-friendly and non-depleting in nature [3]. This generation is continue is face many important improvements in energy generation attributing to the advancement of this NCES, which are clean and eco-friendly alternative source of power [4].

NCES, especially solar and wind power are befitting eloquent generation technologies developing at a consistent pace in the power sector to meet the energy demand. The present Indian NCES power situation is illustrated in fig.1, which presents the aggregate installed capability of NCES in India which is 36.2%, where Wind accounts around 10.1% and solar contributes 9.8%. Fig.2 reveals the India's wind power capacity installed in total, where 28.3GW has been reached earlier. Further, The Fig.1 displays the India's absolute equipped power capacity of 372 GW and the percentage contribution of all NCES from MNRE reports 2020. [5]- [7].

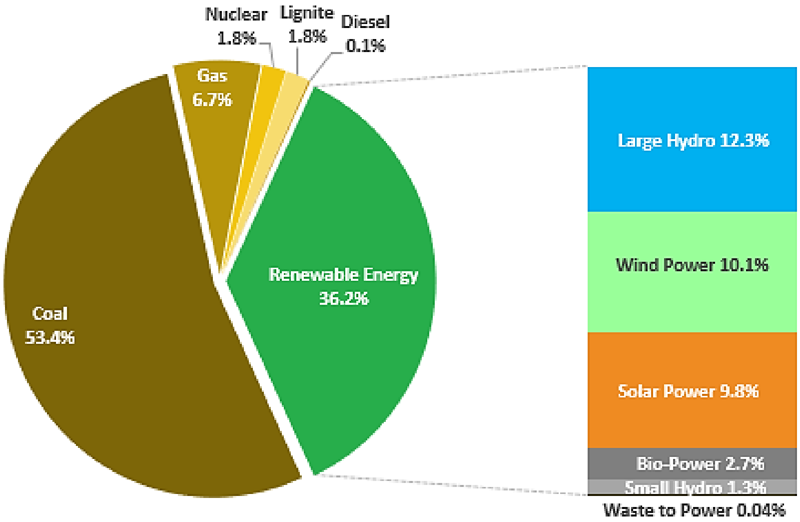

Fig. 1 *India's total installed power capacity*

The capacity addition of solar and wind utility scale for past 5 years are recorded and shown in Fig.2. Hence, HRES namely solar-wind provides community power which includes residential and rural electrification by means of grid integration. Moreover, with advantages like higher reliability, efficiency and better performance. It acts as a potent alternative to the main utility grid in case of emergency and weak grids. However, the intermittent nature of NCES leads to power deficit and voltage fluctuation problem at the load. [8]-[12].

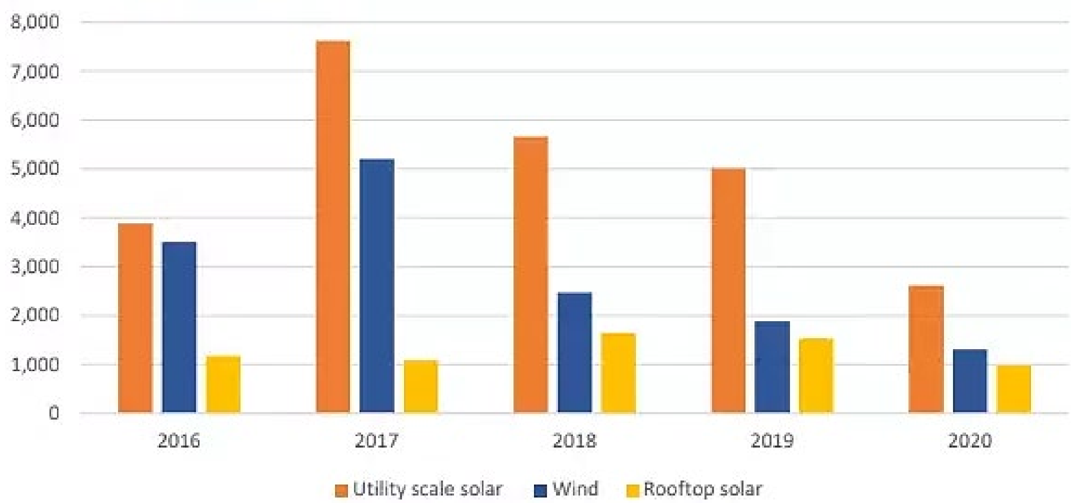

Fig. 2 *Capacity addition of solar and wind for last 5 years*

The aforementioned problems can be solved with help of necessary power converters with appropriate control methods. In addition, the power generated by the NCES has to store in order to supply during energy generation deficits. The battery energy storage is incorporated which charges during excess supply and discharges during the supply demand. [13]- [15]

Due to environmental factors, the output power generated by the PV cell and wind varies and intermittent in nature. In order to maintain constant dc voltage, an efficient and suitable controller is required [16-18]. Several control methods and control algorithms for maximum power point tracking are proposed in several literatures. The most commonly employed method is Perurb and Observe (P&O) because of its easy and simple implementation. Despite the advantages of P&O method, it has slow response and oscillates during peak point tracking. The Sliding Mode Controller (SMC) is suited to non-linear systems are reported in [19]-[26]. SMC has several advantages like dynamic response, stability, robustness and easy implementation. [27-30]

This paper briefs the design of SMC to track the maximum power point tracking by varying the duty ratio of DC-DC converter thereby maintaining constant DC voltage. The individual simulation model of wind generator, PV generator and the battery model and its performance is analysed for varying irradiance and wind velocity. The SMC is applied to obtain the constant voltage across the DC-DC converter. The performance of HRES using SMC is compared with P&O method. The results prove the suitability of SMC for non-linear systems over P&O method.

2. System Description

The Fig.3 presents the block diagram of the suggested HRES under investigation [22]. The DC-DC converter converts the unregulated DC output voltage from the PV generation system to constant DC voltage to synchronize the common DC link in the proposed system. The wind generator comprises wind turbine and generator unit produces an AC voltage which acts as input to the rectifier circuit which converts the voltage to DC. This pulsating DC output voltage from the rectifier is fed to the DC-DC converter, which regulates and provides the constant output DC voltage in synchronisation with the common DC link. The battery supports the HRES during generation deficits [28-30]. The DC output from DC link is fed the inverter, which feeds the load/grid.

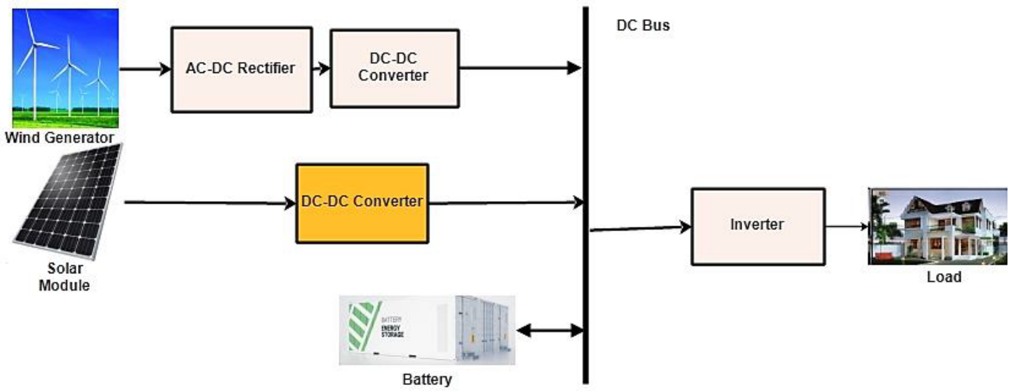

Fig. 3 *Hybrid NCES organisation*

3. The Hybrid NCES System Modeling

The hybrid NCES generation process incorporates a Wind Generation System (WGS) and a Solar Generation System (SGS) and battery to transfer energy to a common DC bus through appropriate power conversion systems. The SMC controller is employed to obtain constant DC voltage from DC-DC converter. The WES comprises a wind turbine driven PMSG, an AC-DC rectifier and a DC-DC converter. The SGS includes of PV array supplying the DC bus through a DC-DC converter. A battery bank is added to overcome the problems of scarce generation. The DC power is delivered to the AC loads through an inverter. The SMC controller cooperates in tracking the maximum power from hybrid NCES.

3.1 Wind Generation

The WGS includes of a wind turbine coupled to the Permanent Magnet Synchronous Generator (PMSG). The assumptions are made that the turbine blades are fixes rigidly to the wind turbine and the pitch angle of the turbine blades is maintained constant, the mechanical power output from the turbine drives the PMSG. The modelling equations are as follows,

The relation between wind velocity and output power of the turbine is given by the following equation

$$P_{out} = (1/2)\rho A_r C_{pow}(\lambda, \beta) V_{\omega}^{3} \quad (1)$$

Cpow - power coefficient; ρ - air density; A_r - swept area of rotor blades; Vω - wind velocity; λ - tip speed ratio; β - blade pitch angle. The power coefficient Cpow is expressed as a function of the tip-speed ratio λ and the blade pitch angle β and the tip-speed ratio λ is given by

$$\lambda = \frac{R\omega_r}{V_\omega} \quad (2)$$

$$C_{pow} = 0.5\left[\frac{116}{\lambda_1} - 0.4\beta - 5\right]\left[e^{-\frac{16.5}{\lambda_1}}\right] \quad (3)$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.089} - \frac{0.035}{\beta^3 + 1}} \quad (4)$$

$$C_{Tr} = C_{pow} / \lambda \quad (5)$$

$$T_{tur} = 1.5 * A_r * C_{Tr} * R * V_\omega^{\ 2} * \rho \quad (6)$$

3.2 PMSG Generator

The dynamic model of the PMSG is derived from the equivalent circuit of the PMSG in the d-q synchronous rotating reference frame in which the q-axis is 90 degrees ahead of the d-axis with respect to the direction of rotation from Fig.4.

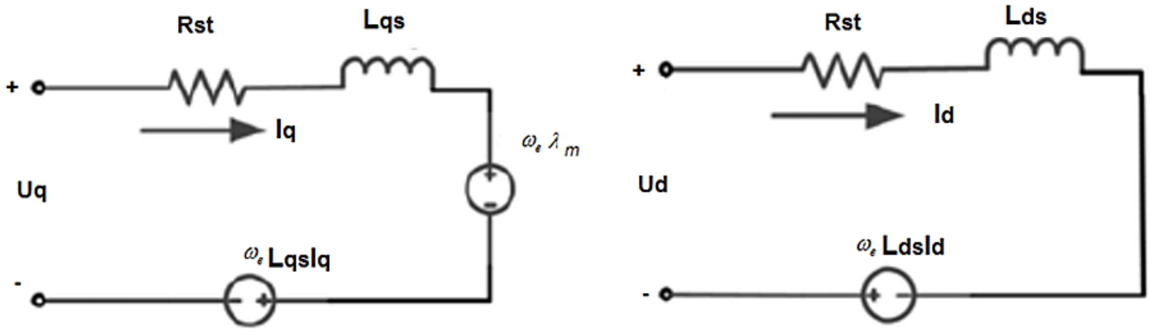

Fig. 4 *PMSG equivalent circuit*

$$\frac{di_d}{dt} = \frac{1}{L_{ds} + L_{ls}}((-R_{st}i_d + \omega_e(L_{qs} + L_{ls})i_q + U_d)) \quad (7)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs} + L_{ls}}(-R_{st}i_q + \omega_e(L_{ds} + L_{ls})i_d + \psi_f) + U_q) \quad (8)$$

$$T_{em} = 1.5p(L_{ds} - L_{ls})i_d i_q + i_q\psi_f \quad (9)$$

Where L_{ds}, L_{qs} are the PMSG inductances in synchronous rotating reference frame are, R_{st} is the stator resistance, ω_e - electrical rotating speed of the generator.

3.3 Three-Phase Rectifier

The 3- phase rectifier converts the AC output from the PMSG into pulsating DC whose output voltage V_{recti} is given by (10).

$$V_{recti} = 1.65V_{\max} \quad (10)$$

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3.4 DC-DC Converter

The intermittent nature of wind forces the PMSG output to vary resulting in pulsating dc output voltage from the rectifier. The DC-DC converter regulates its output voltage constant DC voltage using SMC to meet requirement of the inverter. The relationship between the input and output voltage is represented by (11) Where duty ratio is represented as δ.

$$U_{out} = U_{in}(1-\delta) \tag{11}$$

3.5 Solar Module

The correlation between voltage and current is given by (12)

$$I_s = I_{ph} - I_o(e^{(U+iR_s/n_s U_T -1)} - 1) - \frac{(U+iR_S)}{R_{sh}} \tag{12}$$

The power output of the solar cell is given by (13)

$$P_S = V_S I_S \tag{13}$$

Where I_o - Diode Reverse saturation current (A); U - Terminal voltage; R_s - Panel series Resistance; R_{sh} - Panel shunt Resistance; n_s *- no of* series connected cells in panel , I_{ph} - Photo current (A); U_T - Junction terminal voltage, *Ps*-output power of solar cell; Is-output current of solar cell; Vs- output voltage of the solar cell.

3.6 Battery Energy Storage System (BES)

The most essential part of HRES is the BES system. It provides best solution to hybrid wind-solar system. It augments the need to meet increasing demand for power during the intermittent environmental factors. It transfers the excess energy during weak load or excess supply from the HRES to peak points. This energy storage aids in balancing distribution of energy in power system. It acts as a buffer either as load or generator meeting the supply to demand ratio. The schematic BES system is shown in Fig. 5.

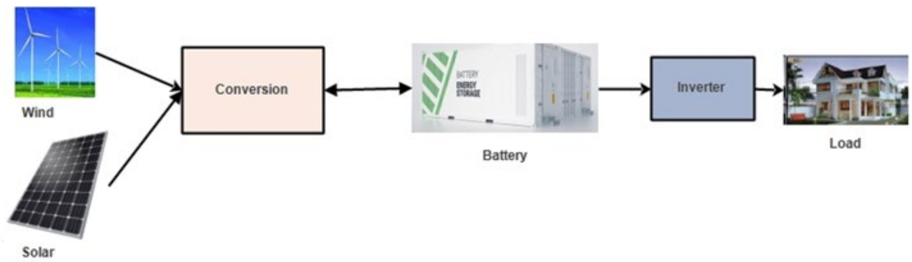

Fig. 5 *BES system*

3.7 Three-phase Inverter

The 3-phase inverter converts the DC voltage at the DC bus into AC employing Sinusoidal Pulse Width Modulated (SPWM) technique. The (14) represents the output voltage of the inverter (rms) while t_{on} is the turn-on time of the switch,

$$V_0 = V_S \sqrt{\left(\sum_{n=1}^{2p} \frac{2t_{on}}{T}\right)} \tag{14}$$

The modulation index is given by (15)

$$m_a = \frac{V_{con}}{V_C} \tag{15}$$

Where,
V_{con} – max. value of (sine) control signal
V_c - max value of (triangular) carrier signal

4. Sliding Mode Controller (SMC) for Interlink Converter

The system with variable structure has a potential feature for control applications like in the sliding mode. In this mode, it appears on the surface thereby system does not get affected by the parameter variations and intermittence. The SMC design involves the choosing of appropriate sliding mode, the sliding surface is decided by adding the error of the output power and output error integral to obtain zero steady state is shown in Fig.6.

The suitable choice of SMC is given by (16)

$$u = u_{eq} + N * sign(sf) \tag{16}$$

The SMC structure is defined by (17)

$$u = \delta(n+1) \quad , \quad u_{eq} = \delta(n) \tag{17}$$

Where u_{eq} – equivalent control; the motion of the trajectory along sliding surface is decided by it; *δ (n) , δ(n+1) – duty cycle at n,(n+1)* th *instant; N*- maximum controller output; *sf*- switching function.

To achieve MPPT, (18) must be

$$\frac{P_S(n)-P_S(n-1)}{I_L(n)-I_L(n-1)} = 0 \tag{18}$$

$$\frac{P_s(n)-P_s(n-1)}{I_L(n)-I_L(n-1)} = \frac{I_L(n)^2 R_s(n) - I_L(n)^2}{I_L(n)-I_L(n-1)}$$

$$= I_L(n)\left[2R_s(n) + I_L(n)\frac{R_s(n)-R_s(n-1)}{I_L(n)-I_L(n-1)}\right] = 0$$

$$\Rightarrow 2R_s(n) + I_L(n)\frac{R_s(n)-R_s(n-1)}{I_L(n)-I_L(n-1)} = 0 \tag{19}$$

The sliding surface is decided based on eq. (19) so as to confirm the right operation of the system at maximum power point, where R_s is the resistance of the solar panel and is represented by (20)

$$R_s = \frac{V_s(n)}{I_L(n)} \tag{20}$$

The equation (21) defines the switching function of the sliding surface

$$sf(n) = 2R_s(n) + I_L(n)\frac{R_s(n)-R_s(n-1)}{I_L(n)-I_L(n-1)} \tag{21}$$

To obtain maximum power point, the equivalent control is obtained by satisfying the following condition.

$$sf = 0$$

$$u_{eq} = 1 - \left(\frac{V_s(I_L)}{V_{out}}\right) = \delta(n) \tag{22}$$

The δ ranges from 0 to 1, therefore the suggested control signal,

$$\delta(n+1) = \begin{cases} 0 & \delta(n) + N * sign(sf) \geq 1 \\ \delta(n) + N * sign(sf) & in\ the\ rest \\ 0 & \delta(n) + N * sign(sf) \leq 0 \end{cases} \quad (23)$$

δ (n) is ensured to be maintained between 0 and 1 to reduce chattering.

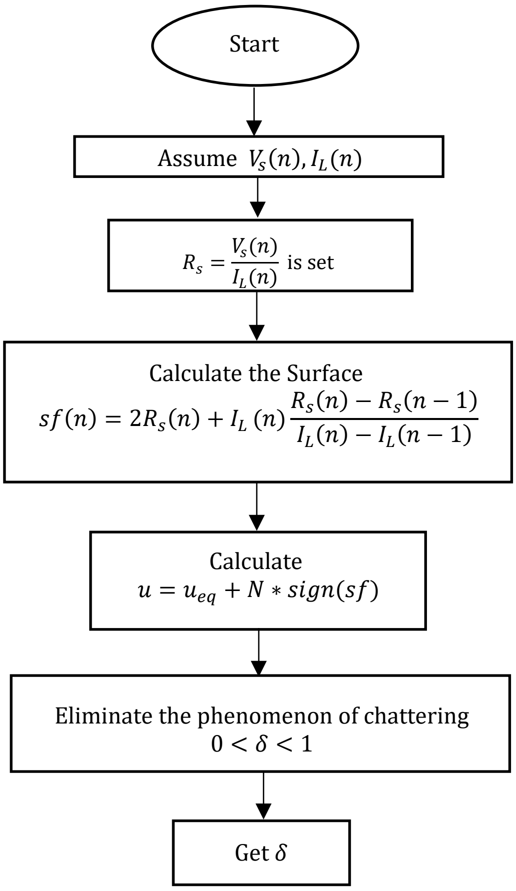

Fig. 6 *SMC algorithm for hybrid energy systems*

5. Results and Discussion

The suggested hybrid NCES system namely solar, wind, battery system is considered for analysis. The parameters illustrated in Appendix 1 are utilized for simulation. The simulation model is developed in Matlab/Simulink. The different components of wind generator, solar generator, Battery, DC-DC converter and 3-phase inverter and electrical grid are modelled individually. The SMC controller is developed to obtain MPPT for hybrid energy system.it optimizes the wind-PV system to attain the optimal duty ratio. The simulation results are presented and compared with the conventional P&O optimization algorithm.

5.1 PV System

The current and power variation with respect to voltage for different irradiance profiles is depicted in Fig. 7. The PV voltage, current and power corresponding to irradiance is as shown in fig.8. It is observed that PV array develops a voltage of about 85V and current of around 2A. The maximum power obtained using SMC controller is found to be 200W at 1000W/m^2 irradiance.

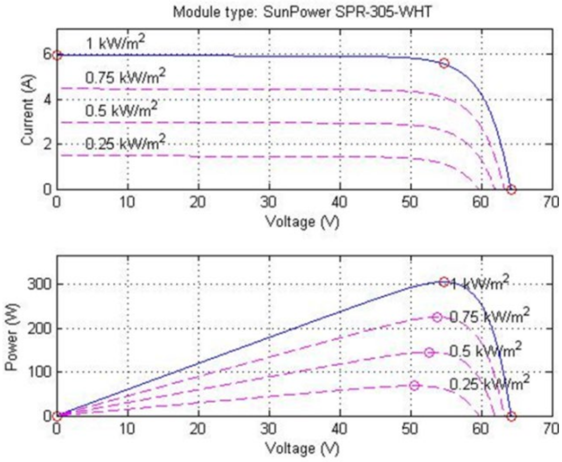

Fig. 7 *I-V and P-V characteristics of solar system*

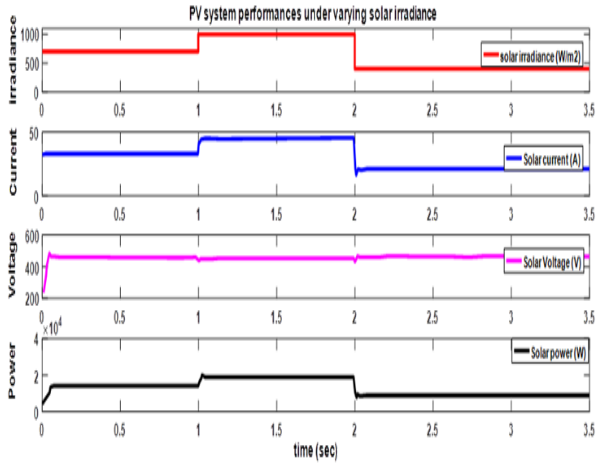

Fig. 8 *PV performance parameter power, voltage and current*

5.2 Wind Generation System

The output characteristics for different rotor speed with varying wind velocities are as presented in Fig.9. It is observed that the output power of 2000W is obtained at 12m/s. The performance parameter the generated voltage, current and power are shown in Fig.10. The SMC controller helps to maintain the dc link voltage constant. The battery system is developed and simulated in Matlab. The solar and wind power is noted and illustrated is fig.11. The DC link voltage and reference is as shown in fig.12

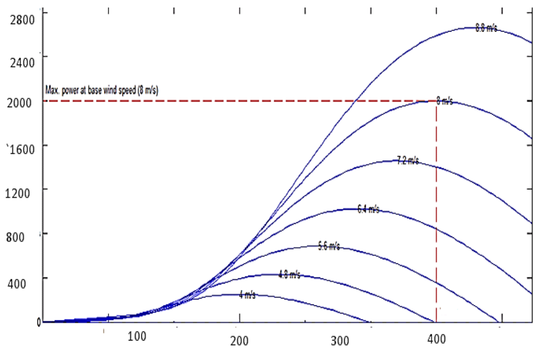

Fig. 9 *Output characteristics of wind*

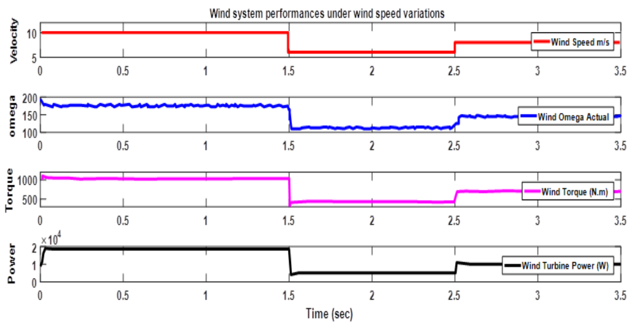

Fig. 10 *Wind performance parameter power, voltage and current*

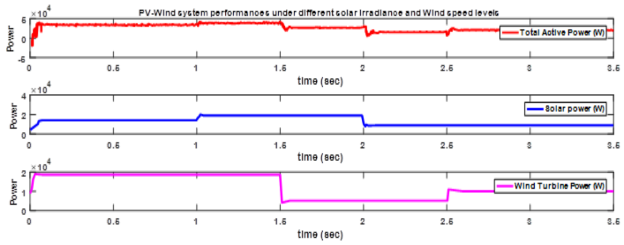

Fig. 11 *Power output at wind, solar*

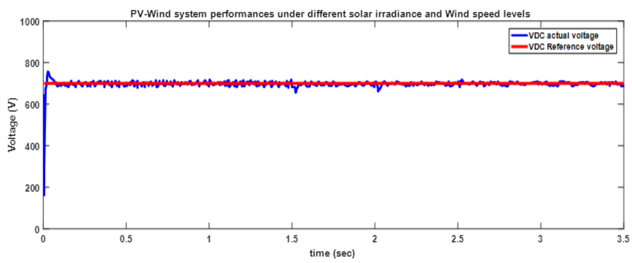

Fig. 12 *DC link voltage*

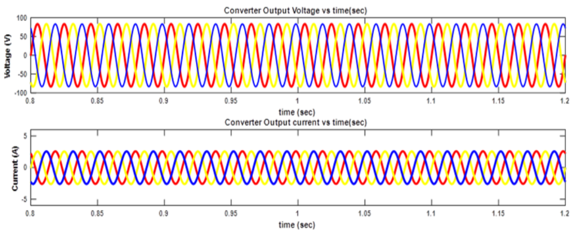

Fig. 13 *Inverter output voltage and current*

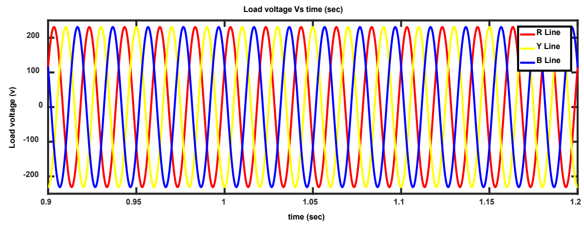

Fig. 14 *Load voltage*

The output voltage and current of the 3-phase inverter is presented in fig.13. The load voltage, current and power at the PCC is described in Figs.14-16. It is observed that the load power is about 150W. The output at 3-phase inverter is stepped up using transformer and fed to the grid. The grid voltage and current (phase) are illustrated in fig.17.

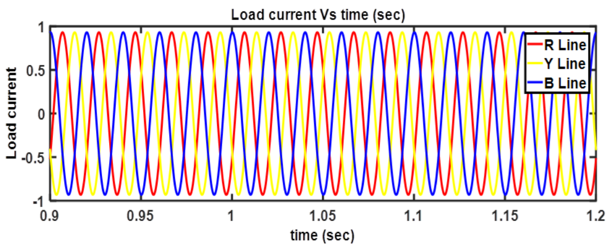

Fig. 15 *Load current*

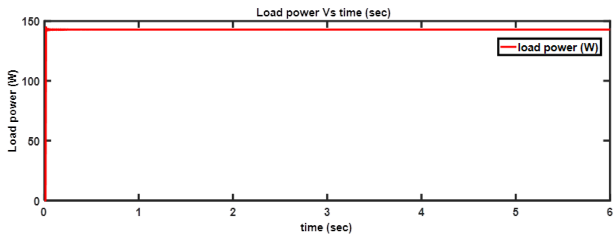

Fig. 16 *Load power*

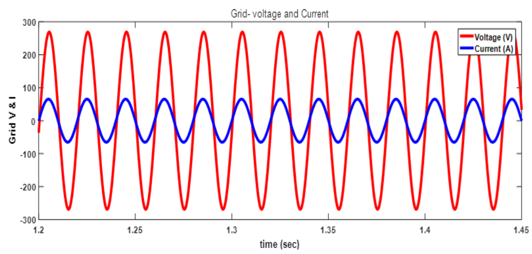

Fig. 17 *Grid voltage and current*

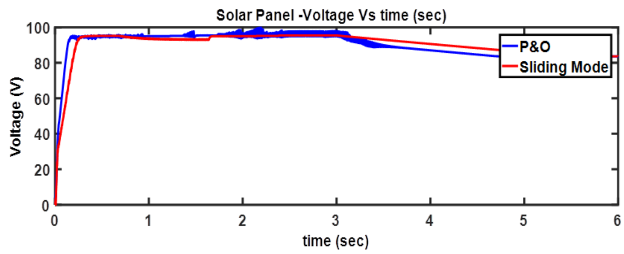

Fig. 18 *PV voltage with SMC and P&O method*

The performance of SMC controller for wind and PV system is developed and compared with P&O algorithm.

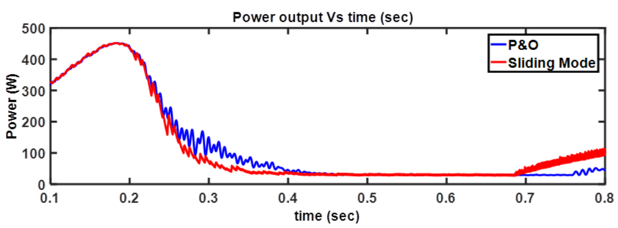

Fig. 19 *PV power with SMC and P&O method*

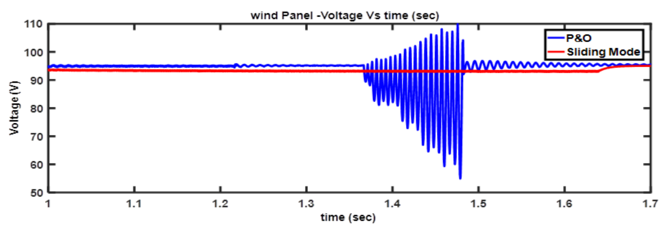

Fig. 20 *Wind voltage with SMC and P&O method*

Solar voltage and power are compared with the P&O optimization method. It is observed that SMC controller outperforms the P&O controller. Figs.18-21 shows comparison results for both PV and wind systems.

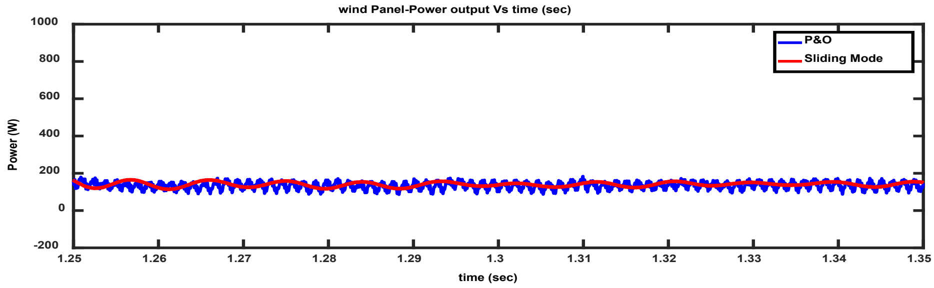

Fig. 21 *Wind power with SMC and P&O method*

6. Conclusion

In this study, the suggested HRES is formulated to obtain the objective of extracting the maximum power over an wide choice of wind velocities and solar intensities and deliver an uninterruptable power to meet the claim Exclusively in rural areas where the possibility of conventional electric grid are remote.The system components solar cell, DC-DC converter, wind turbine, PMSG generator, 3-phase inverter are developed. The performances of the hybrid NCES system are investigated. The charging and discharging o the BES system is analysed and presented. The maximum power is tracked using SMC controller from HRES. The DC-link voltage is regulated and maintained constant using SMC. The SMC results are compared with conventional P&O method. The observed results confirm the potential of SMC controller.

Appendix-A

PV Array	
irradiance	1000
V_{oc}	90
I_{sc}	2.02
V_{mp}	70.4
I_{mp}	1.93
Wind Generator Parameters	
Rated power	1500 W
Rated Voltage, Rated Frequency	440V, 50Hz
Stator, Rotor Resistances	0.006, 0.1248 p.u.
Control Parameters	
DC Bus voltage regulator gains k_p	1.1
DC Bus voltage regulator gains k_i	27.5
Grid-side convertor voltage regulator gains k_i	2
Grid-side convertor voltage regulator gains k_p	1
Grid-side convertor current regulator gains k_i	50
Speed regulator gains k_p	5
Speed regulator gains k_i	1
Pitch controller gain k_p	15
Load	
V_{rms}(phase –to- phase voltage)	254.04
Frequency	50
Active Power P (W)	150
Battery	
Battery Type	Nickel metal hybrid
Rated Capacity	60Ah
Nominal Voltage	12

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *P.Suresh, D.Lenine;* ***data collection:*** *P. Sai Sampath Kumar;* ***analysis and interpretation of results:*** *P.Sai Sampath Kumar, P.Suresh ;* ***draft manuscript preparation:*** *P.Sai Sampath Kumar, P.Suresh. All authors reviewed the results and approved the final version of the manuscript.*

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