

Control & Implementation of Fuzzy Based DFIG Wind Power Generators in Unbalanced Micro grids

Dr. DINESH KUMAR

¹

PG Student, Dept. of EEE, Sri Padmavathi Mahila University, Tirupati .

² Ph.D & Assistant Professor, Dept. of EEE, Sri Padmavathi Mahila University, Tirupati

Abstract—This work presents a proposed power system with a diesel generator (DG), wind energy conversion system and solar photo voltaic (PV) system. The proposed power system with its control techniques, regulates the loading of DG to achieve a low specific fuel consumption with the help of wind energy conversion systems (WECS) and SPV system. The doubly fed induction generator (DFIG) is used in WECS system. The WECS system consists of two voltage source converters (VSCs) for the system control. One converter is FUZZY based RSC Control Strategy(RSC), which helps in achieving maximum power point tracking of the wind turbine. Another one is the generator side converter (GSC), which helps in regulating DG generation while maintaining WECS generator as well as Diesel generator currents balanced, unbalanced and harmonics within the requirement of the IEEE-519 standard at different load conditions. The system envisages energy storage by connecting a battery bank at the DC bus of DFIG. The battery bank provides buffer storage. To increase optimal operation, solar PV system with MPPT technique also integrated with DG system, and SPV system with MPPT algorithm maintain DC link voltage. The proposed power system is modelled using MATLAB Sim-power-system tool box and proposed system performance results are presented under variation of linear loads, nonlinear loads, unbalanced loads.

Index Terms—

Wind Turbine, doubly fed induction generator (DFIG), diesel generator, solar photovoltaic array, bidirectional buck/boost DC-DC converter, battery energy storage, power quality.

1. INTRODUCTION

Diesel generators (DGs) are very popular for the decentralized power generation as well as backup power in the urban housing society for the following reasons [1]-[3].

- DGs are portable and dispatchable.

- They are of lower capital cost.
- DGs maintenance is easier.
- They have higher conversion efficiency as compared to other sources of energy resulting in low specific greenhouse gas emission.

For the above reasons, they are widely used for the power distribution of islands, commercial and military ships etc [4]. However, DGs suffer from the higher running cost along with noise and air pollution. The running cost is dependent on amount of fuel consumption based on the power generation. This cost is minimized by installing renewable energy (RE) sources such as wind, solar and biomass etc. Moreover, RE based power sources are pollution free and abundant in nature. Among RE sources, wind and solar are considered to be more popular because of their reduced cost and technological advancements [5], [6]. Wind turbines are mainly categorized as fixed speed and variable speed type. Fixed speed wind turbines have been used earlier due to their simple operating features. However, they suffer with more power loss. Variable speed wind turbines with doubly fed induction generator (DFIG), are dominantly used for wind energy extraction due to its advantages such as reduced converter rating, less acoustic noise, highly energy efficient and low power loss [7]. Substantial literature on DFIG based wind energy conversion system (WECS) both in standalone [8] and grid connected modes, is available [9]-[11]. In [8], the authors have presented DFIG based WECS operating in standalone with a battery energy storage (BES) connected directly at the DC link. Moreover, the comparative performance with and without BES is discussed. In [9], the authors have described an extended active power theory for effective operation of wind turbine coupled DFIG both in balanced and unbalanced grid conditions. Moreover, the DFIG is controlled with only rotor side converter (RSC). Therefore, the topology suffers from the power quality issues especially during harmonic loads. Liu *et al.* [10] have investigated the influence of phase locked loop parameters and grid strength on the stability of DFIG wind farm in grid connected mode. However, an experimental validation has

not been performed. In [11], the authors have discussed a synchronization control method for smooth connection of DFIG to the grid. Moreover, it has been implemented on a modified IEEE

39 bus system using real time simulation platform. However, hardware realization has not been done. In other side, there has been increasing power generation through solar photovoltaic (PV) array world wide. The solar energy conversion system (SECS) can be single stage or double stage. Some of the literature regarding solar PV system is reported in [12], [13]. Shah *et al.* [12] have demonstrated the single stage SECS connected to the utility grid. Moreover, a fundamental current extraction technique based on second-order generalized integrator with frequencylocked loop has been implemented for voltage source converter (VSC). In [13], the authors have presented the double stage SECS interacting to the grid. In addition, an adaptive algorithm of fast zero attracting normalized least mean fourth has been implemented for VSC to improve the power quality issues.

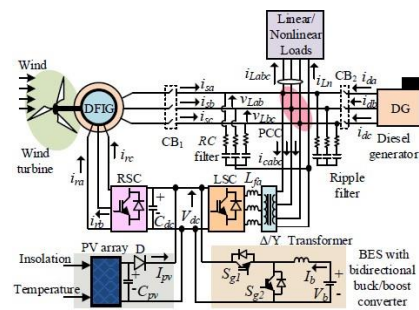
The operation of WECS and SECS separately, is not economical and reliable because of their intermittency. Therefore, the integration of both wind and solar sources, improves reliability of power generation [14], [15]. Morshed *et al.* [14] have presented wind-PV system with fault ride through capabilities. In its topology, the solar PV array is connected at the DC link of DFIG based WECS through a boost converter and a DC-DC converter. However, it increases the switching losses and cost, because of additional DC-DC converter along with grid side converter. In [15], the authors have demonstrated the windsolar PV system with BES in standalone mode. In its configuration, the solar PV array is connected at the DC link of wind turbine driven DFIG through a boost converter. However, the current through BES is not controlled, because it is directly connected at the DC link. Further, the microgrids based on DG, wind and solar sources have been developed and reported in the literature [16]-[18]. In [16], the authors have discussed the capacity of BES for a microgrid based on wind, solar and diesel sources that are located in an island. However, optimal fuel operation of DG has not been discussed. In [17], the authors have demonstrated a wind-diesel microgrid for fuel efficient zone with BES.

However, the BES current is not controlled due to

lers. In any microgrid, the BES plays vital role during the mismatch of generation and demand. Moreover, it helps in extraction of maximum power both from wind and solar, especially when the generation is more than the demand. There are many maximum power point tracking (MPPT) techniques discussed in the literature, both for wind and solar to extract maximum power corresponding to particular wind speed and insolation, respectively [12], [13], [15], [19], [20].

This work presents a microgrid based on wind turbine driven DFIG, DG and solar PV array with BES, in order to minimize the fuel consumption of DG. In this, the DG is designed to deliver the base load requirement of a particular household locality. The main contributions of this study are on the control aspects of the scheme, which are as follows.

- A novel generalized concept is used to compute the reference DG power output for the DG to remain operating in optimal fuel consumption mode.
- The load side converter control (LSC) is designed to control DG along with the power quality issues such as load unbalance compensation, harmonics compensation and reactive power compensation.
- The RSC control is designed to extract maximum power from the wind turbine.
- The BES is connected to the common DC bus of back-back connected VSCs through a bidirectional buck/boost DC-DC converter. It aims to provide path for excess stator power of DFIG. Moreover, a solar PV array is directly connected at DC bus.
- The bidirectional buck/boost DC-DC converter control is designed in a way to extract maximum power from the solar PV array and to control the current through BES.
- A modified perturb and observe (P&O) MPPT algorithm is presented to obtain maximum power from a solar PV array.
- This microgrid configuration is implemented with minimum number of converters, thereby reducing the total system cost and switching losses.
- The DFIG stator currents and DG currents are maintained balanced and sinusoidal, as per the IEEE 519 standard.



its direct connection at the DC link. Moreover, the chances of getting away from fuel efficient zone is more due to connection of only one RE source. Venkatraman *et al.* [18] have presented a wind-solardiesel microgrid with BES for certain remote area. However, the optimal operation of DG has been ignored while developing the source and load control--n coupling (PCC). To validate the microgrid operation, tests are performed on a developed prototype in the laboratory.

II. CONFIGURATION OF MICROGRID

The schematic configuration of the microgrid is depicted in Fig.

1. It consists of wind turbine, DFIG, DG, solar PV array, BES, bidirectional buck/boost DC-DC converter, RSC, LSC, interfacing inductors, Δ/Y transformer, linear and nonlinear loads, circuit breakers (CB1 & CB2), DC link capacitor and ripple filters etc. This microgrid is designed to deliver a peak load of 7.5 kW for a particular locality. The wind turbine generator and solar PV array, are designed to deliver a power of 7.5 kW each. In this scheme, the solar PV array is directly connected to DC link, whereas BES is co

The wind-dieselsolar microgrid with BES is modelled and simulated using SimPowerSystems tool box of MATLAB. The system performance is analysed for variable wind speeds, variable insolation, effect on buck boost converter at varying loads and unbalanced nonlinear load connected at point of common connected through bidirectional buck/boost DCDC converter. The DG is comprising of a synchronous generator of 4 pole, internal combustion engine of 4 stroke reciprocating type along with automatic voltage regulator (AVR). A 7.5 kVA DG is selected in line with rated capacity of the wind turbine generator. The design of a wind turbine generator, solar PV array, DG, BES and other components, is carried out based on the literature reported in [12], [15], [17]. Moreover, the design parameters of microgrid, are given in Appendices.

7.5 kVA DG is selected in line with rated capacity of the wind turbine generator. The design of a wind turbine generator, solar PV array, DG, BES and other components, is carried out based on the literature reported in [12], [15], [17]. More over, the design parameters of microgrid, are given in Appendices.

Fig.2. DFIG based microgrid.

The complete description of control algorithms of RSC and LSC, MPPT algorithm of solar PV array, bidirectional buck/boost DC-DC converter, are given in following subsections.

A. Control Algorithm for RSC

The control algorithm of RSC, is depicted in Fig.

connected through bidirectional buck/boost DCDC converter. The DG is comprising of a synchronous generator of 4 pole, internal combustion engine of 4 stroke reciprocating type along with automatic voltage regulator (AVR). A

1. The RSC is used to supply the reactive power requirement of DFIG

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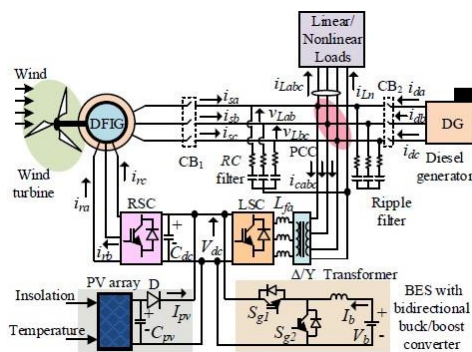


Fig. 1. DFIG based microgrid.

III Developing Control for the New Scheme.

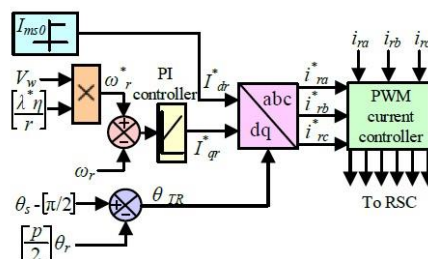
The schematic configuration of the microgrid is depicted in Fig.

4.8. It consists of wind turbine, DFIG, DG, solar PV array, BES, bidirectional buck/boost DCDC converter, RSC, LSC, interfacing inductors, Δ/Y transformer, linear and nonlinear loads, circuit breakers (CB1 & CB2), DC link capacitor and ripple filters etc. This microgrid is designed to deliver a peak load of 7.5 kW for a particular locality. The wind turbine

Fig.3. RSC control algorithm.

and also, to regulate the speed for achieving MPPT from the wind turbine. The fieldoriented vector control (FOVC) is used for RSC to generate the switching pulses, as shown in Fig.

4.9. In FOVC, direct axis and quadrature axis components of rotor currents (I^*_{dr} , I^*_{qr}) represent reactive and active components, respectively. The I^*_{dr} is corresponding to no load magnetizing current (I_{ms0}) of DFIG, which is computed as [21],



generator and solar PV array, are designed to deliver a power of 7.5 kW each. In this scheme, the solar PV array is (1)

$$I_{ms0} = \frac{\sqrt{2}V_L}{\sqrt{3}X_m}$$

where X_m denotes the magnetizing reactance of the machine and V_L is the line voltage at the machine terminals.

The I^*_{qr} is estimated by passing the speed error through proportional and integral (PI) controller as depicted in Fig. 4.9 and it is derived as,

$$I^*_{qr(k)} = I^*_{qr(k-1)} + K_{p\omega}(\omega_{err(k)} - \omega_{err(k-1)}) + K_{i\omega}\omega_{err(k)} \quad (2)$$

where $K_{p\omega}$ and $K_{i\omega}$ represent proportional and integral constants of PI speed controller, respectively.

The $\omega_{err(k)}$ and $\omega_{err(k-1)}$ denote speed error at k th and $(k-1)$ th instants, respectively.

The $\omega_{err(k)}$, is obtained as,

$$\omega_{err(k)} = \omega^*_{r(k)} - \omega_{r(k)} \quad (3)$$

where $\omega^*_{r(k)}$ and $\omega_{r(k)}$ denote the reference and sensed rotor speed of DFIG at k th instant, respectively.

The reference rotor speed is obtained from the tip speed ratio MPPT control [19] as,

$$\omega^*_r = \eta \lambda^* V_w / r \quad (4)$$

where V_w is wind speed, λ^* is optimal tip speed ratio, r represent wind speed, optimal tip speed ratio, gear ratio and radius of wind turbine, respectively(8)

$$\theta_{TR} = \left(\theta_s - \frac{\pi}{2} \right) - \left(\frac{p}{2} \right) \theta_r$$

The rotor transformation angle (θ_{TR}) is computed as,

$$\beta \text{ takes maximum value when BES voltage falls to its minimum value (} V_{bmin} \text{). The } \beta \text{ is of the form a} \quad (5)$$

where s is obtained from phase locked loop and r is computed from the sensed rotor speed as,

- It regulates the DG power within the range of PD_{min} to PD_{max} to achieve optimal fuel consumption. Where PD_{min} and PD_{max} refer to minimum and maximum DG power output in pu for optimal fuel consumption.

directly connected to DC link, whereas BES is connected to DC link through a modified indirect vector control based on voltage-oriented reference

frame, is used to generate the reference currents as shown in Fig.

3. In this, both DG and DFIG stator currents are added and controlled to extract maximum power from the DFIG and to regulate the DG power within the range for optimal fuel consumption. The d-axis component of LSC is obtained as,

$$I^*_{dg} = I^*_{dd} + I^*_{dw} \quad (7)$$

where I^*_{dd} , I^*_{dw} denote the

d-component current of DG and DFIG, respectively. It is noted that the saturation block is placed before the I^*_{dd} component to operate the DG in optimal fuel efficient zone at change in load, as depicted in Fig.

3. In this work, a generalized concept is used to calculate the DG power based on state of the BES. The reference DG power in pu (P^*_D) is computed as,

$$P^*_D = P_{Dmin} + k_1 \beta$$

Here the value of β varies from 0 to 1. The minimum value of β is achieved when BES is charged to maximum voltage (V_{bmax}) whereas its minimum value (V_{bmin}). The β is of the form a

$$\beta = \frac{V_{bmax} - V_b}{k_2} \quad (9)$$

$$\theta_r = \int_0^t (\omega_r) dt$$

Finally, reference rotor currents (i^*ra , i^*rb and i^*rc) are derived from I^*qr and I^*dr using an angle of transformation θ_{TR} , as depicted in Fig.

2. These reference currents along with sensed rotor currents (ira , irb and irc), are applied to pulse width modulation (PWM) controller to produce RSC gating signals.

B. Control Algorithm for LSC

(6)

The LSC control algorithm is depicted in Fig.

3. The LSC is controlled to achieve the following objectives. (10)

- It maintains the DG and DFIG stator currents sinusoidal and balanced.

where V_L and V_{ADG} represent line voltage at PCC and VA rating of DG, which is chosen as a base value. The I^*dw is computed as,

$$I^*_{dw} = \left(\frac{L_m}{L_s} \right) I^*_{gr} \quad (11)$$

The DG currents (ida , idb and idc) are transformed to Id and Iq using angle of transformation (θ_s), which is obtained from PLL as shown in Fig.

3. The q -

ly same as Iq of DG. The I^*dg and I^*qg are multip

lied with in-

phase and quadrature unit templates, respectively a axis component of LSC current (I^*qg) is numerical

and then added together to generate current references (i^*ga ,

i^*gb and i^*gc). The unit templates are obtained from phase voltages (v_a , v_b and v_c), as shown in Fig.

3. Unit templates of inphase components are obtained as,

$$u_{ap} = \frac{v_a}{V_m}, u_{bp} = \frac{v_b}{V_m}, u_{cp} = \frac{v_c}{V_m} \left\} \right.$$

Fig.6. MPPT algorithm of solar PV array.

where, V_m denotes the peak of phase voltage at PC C, which is computed as,

$$V_m = \{2(v_a^2 + v_b^2 + v_c^2) / 3\}^{1/2} \quad (13)$$

The unit templates of quadrature components, are obtained from in-phase components as,

In (8) and (9),

$k1$ and

$k1$ is selected such that P^*D attains its maximum limit of optimal fuel consumption as β tends to unity. Moreover, the value of

$k2$ is selected such that the β attains unity at V_{bmin} . In this work, the chosen values of $PDmin$, $PDmax$, V_{bmax} , V_{bmin} ,

$k1$ and

$k2$ are mentioned in Appendices.

From (8), the I^*dd is computed as,

$k2$ represent constant parameters. The value of

$$I^*_{dd} = \left(\sqrt{\frac{2}{3}} \right) \times \left(\frac{P^*_D \times V_{ADG}}{V_L} \right)$$

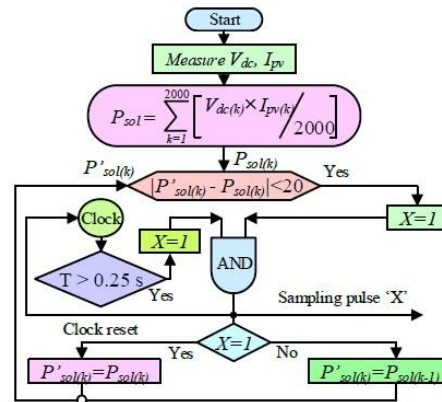
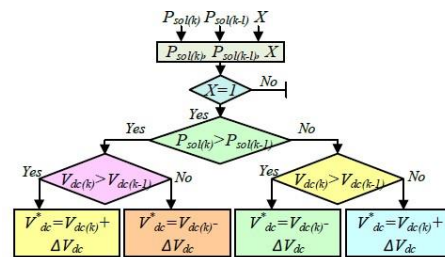


Fig. 5 Sampling pulse generation.



(12)

given to variable 'X'. It varies between digital bits 0 and 1. In Fig.

4, the first step is to get the information of DC link voltage or solar PV voltage (V_{dc}) and solar PV current (I_{pv}) at k th instant and computation of instantaneous solar power. The second step is the deter

mination of running average solar power (P_{sol}), which performs the same function as filtering. In case

if the absolute difference between the running averaged power (P_{sol}) and previously sampled power (P'_{sol}) is less than 20 W combined with minimum time delay of

0.25

seconds from previous sampling, the control senses that the steady state has arrived. On sensing the steady state, the output of the sampling pulse 'X' becomes

'1'. The sampling pulse decides the instantaneous change in reference DC link voltage (V^*_{dc}) or solar PV MPPT voltage. The value of V^*_{dc} is updated only if sampling pulse becomes '1'. This is clearly evident from Fig.

5 that depicts the modified P&O MPPT algorithm.

Once X becomes '1', the MPPT algorithm checks for $P_{sol}(k) > P_{sol}(k-1)$. If it is yes, then it again checks for $V_{dc}(k) > V_{dc}(k-$

1). If it is also

yes, then, the new reference DC link voltage becomes $V^*_{dc} = V_{dc}(k) + \Delta V_{dc}$. Where ΔV_{dc} denotes the

small incremental change in DC link voltage. The

other scenarios are evident from the Fig. 5.

The bidirectional buck/boost DC-DC converter control, is demonstrated in Fig.

Finally, the generated reference currents and sensed currents (i_{ga} , i_{gb} and i_{gc}) are applied to PWM controller to produce pulses for LSC, as depicted in Fig. 3.

C. Solar PV Array MPPT Algorithm and Bidirectional Buck/Boost DC-DC Converter Control

The bidirectional buck or bidirectional boost DCDC converter is used to regulate the DC link voltage

by controlling power flow through the BES. By doing

so, the solar MPPT is achieved. In this, a modified

perturb and observe (P&O) algorithm is used, which

consists of sampling pulse generation (X) and subsequently

estimation of reference DC link voltage

(V^*_{dc}) as depicted in Figs. 4-5, respectively. Fig.

4 illustrates various steps involved in the generation

of sampling pulse 'X'. Here, the sampling pulse is a name

$$\left. \begin{aligned} u_{aq} &= -\frac{u_{bp}}{\sqrt{3}} + \frac{u_{cp}}{\sqrt{3}}, u_{bq} = \frac{\sqrt{3}u_{ap}}{2} + \frac{u_{bp} - u_{cp}}{2\sqrt{3}}, \\ u_{cq} &= -\frac{\sqrt{3}u_{ap}}{2} + \frac{u_{bp} - u_{cp}}{2\sqrt{3}} \end{aligned} \right\} \quad (14)$$

6. The outer proportional integral (PI) controller of the bidirectional windup (PI+A) controllers, values of * dqr I + + can be obtained suitably from errors between the reference and measured signals of the two powers. As aforementioned, the Notch filters are utilized to reject the negative sequence components. Nonetheless, the real response and efficacy of digital Notch filters are not entirely flawless; thus the SCC, containing the two PI controllers, is designed for combining with the Notch filters to can remove thoroughly the negative sequence components of rotor current. In SFOC, with dqr I -- = 0, ψ qr + = 0 and, the rotor current now can be defined by Besides, the output values of the SCC are * dqr I + - ,

6. The inner PI controller is used to track the reference battery current. Moreover, the output of the inner PI controller is the duty ratio (R) of the bidirectional buck/boost DC-DC converter. From Fig. 6, the reference battery current (I*b) is obtained as

6, the reference battery current (I*b) is obtained as

$$I_{b}^{*}(k) = I_{b}^{*}(k-1) + K_{pb}(V_{dc}^{*}(k) - V_{dc}(k-1)) + K_{ib}V_{dc}^{*}(k) \quad (15)$$

Where, error of the DC link voltage at kth instant is $e_{dc}(k)$. Here $V_{dc}^{*}(k)$ and $V_{dc}(k)$ represent the reference DC link voltage and sensed DC link voltage at kth instant, respectively. K_{pb} and K_{ib} denote the proportional and integral constants of the outer PI controller.

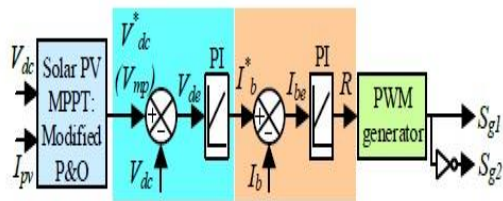


Fig. 7.

Control of bidirectional buck or bidirectional boost

so it also has function as a current subcontroller for the PI-F and PI-FUZZY controllers to help regulate the positive sequence components of rotor current. Meanwhile, note that negative sequence components of the rotor current will boost the power rating of RSC if they are utilized in stabilizing the two output powers of DFIG. From, the output active power P_s and reactive power Q_s in stator are computed as follows:

Structure of the PI-FUZZY hybrid controller in

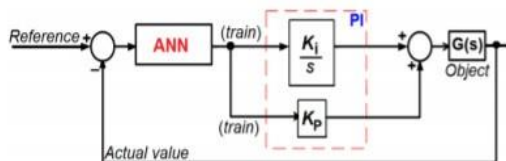


Fig. 8 Design diagram of the PI-FUZZY controller

t converter.

integral constants of the outer PI controller. Besides,

$$R_{be}(k) = R_{be}(k-1) + K_{pr}(I_{be}(k) - I_{be}(k-1)) + K_{ir}I_{be}(k) \quad (16)$$

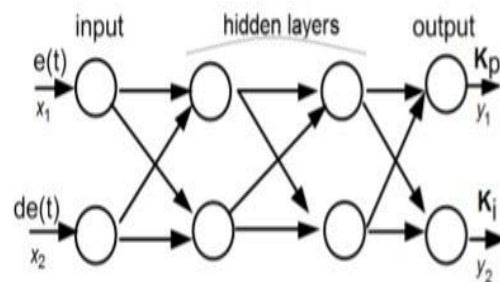
es, the duty ratio (R) of the bidirectional DCDC converter, is computed as,

$$(16)$$

Where, error of the battery current at kth instant is

$$I_{be}(k) = I_{b}^{*}(k) - I_{b}(k)$$

. Here $I_{b}^{*}(k)$ and $I_{b}(k)$ represent the reference battery current and measured battery current, respectively.



weight value net_q and the output value Z_q of the j th neuron in the

q -th hidden layer are computed, respectively

$$net_q = \sum v_{qj} x_j \quad (17)$$

ery current and sensed battery current at k th instant, respectively. The obtained duty ratio (R) is applied to PWM generator to produce pulses for the switches of the bidirectional buck or bidirectional boost converter.

IV The newly proposed RSCbased scheme with the PI-FUZZY hybrid controller and SCC.

The reference voltage values $* V_{dqr} +$ for the RSC are computed from the outputs of two PI-FUZZY controllers as described in Fig.

4. The PI-FUZZY controllers can enhance remarkably the independence with parametric alterations of the power system in generating the reference signals. Also, using the PI with anti-

the input data $x(k)$ is transmitted forward to generate the value $y(k)$ at the output. Then, the error value $E(k)$ between the reference value in the data set $d(k)$ and the above output value $y(k)$ is transmitted back to the previous layer to update fittingly the weights v_{qj} . The data set utilized for the offline

Fig.

9 Detailed structure of the FUZZY with four layers

The proposed FUZZY in this study utilizing RSC control algorithm for performing an offline training process to determine suitable values for the key two coefficients K_P and K_I of the PI controller. As given in Fig. 6, the FUZZY comprises one input layer, two hidden layers and one output layer. Wherein, the input layer has two neurons as the error value $e(t)$ and its derivative value $de(t)$ of the current as shown in Fig. 4, each hidden layer has two neurons, and the output layer has two neurons as K_P and K_I . The total

$$Z_q = a_h(net_q) = a_h(\sum v_{qj} x_j) \quad (18)$$

Where v_{qj} is the weight gain for the j -th neuron, and $a_h(\cdot)$ is the operational function used for the q -th hidden layer. Then, the total weight value of the i -th neuron in the output layer is expressed, where w_{iq} is the weight gain for the q -th neuron. Lastly, the two coefficients K_P and K_I are defined by respectively; where $a_0(\cdot)$ is the operational function used for the output layer.

$$net_i = \sum w_{iq} Z_q = \sum [w_{iq} \cdot a_h(net_q)] \quad (19)$$

output voltage (V_{dc}), battery current (I_b), battery voltage (V_b), wind speed (V_w), insolation (G), rotor power

$$(20)$$

$$K_P = a_0(net_1) = a_0(\sum w_{1q} Z_q) = a_0(\sum [w_{1q} \cdot a_h(net_q)]) \quad K_I = a_0(net_2) = a_0(\sum w_{2q} Z_q) = a_0(\sum [w_{2q} \cdot a_h(net_q)]) \quad (21)$$

Where operational functions in hidden and output layers are bipolar sigmoid and linear functions, respectively:

phase DG current (i_{da}), aphase PCC voltage (v_{La}), stator currents (i_{sabc}), D

The performance of bidirectional buck or bidirectional boost DC-

$$(22)$$

$$a_0(f) = f \quad (23)$$

If the number of hidden layers is increased, FUZZY may have a better adaptation. In this study, to evaluate the proposed PI-FUZZY algorithm, two hidden layers can be used such as the simplest structure for implementing in simulation. Where the number of hidden layers is more, the training time becomes longer; which can lead to cause noticeable delay in generating the control signal at output layer. So optimization for the number of hidden layers and time delay will be studied in our future work. As shown in Figs. 5 and 6, the BP algorithm has two main steps in transmitting information between layers as follows. Firstly,

training process is $S\{x(k), d(k)\}$, and the goal of the training process is to minimize the error $E(k+1)$

as given. Normally, the offline training process in FUZZY is performed sometimes with several data sets to achieve a good result as desired.

$$E(k+1) = E(k) + 0.5 \sum [d_i(k) - y_i(k)] \rightarrow \min \quad (24)$$

IV Simulation Results for the New DFIG Scheme

The microgrid based on wind turbine driven DFIG, DG and solar PV array with BES, is simulated using MATLAB. Various signals used to analyze the system performance, are rms value of phase voltage (V_r), system frequency (f_L), DFIG rotor speed (ω_r), DG power (P_D), wind power from stator (P_w), solar PV power (P_{s0}), load power (P_L), LSC power (P_{LSC}), DC link voltage

coefficient (C_p), a-phase stator current (i_{sa}), rotor currents (i_{rabc}), a-

phase currents (i_{dabc}), load currents (i_{La} , i_{Lb} and i_{Lc}), neutral current (i_{Ln}) and LSC currents (i_{cab}). The parameters used for the simulation are mentioned in Appendices.

A. Performance of Bidirectional Buck/Boost DC-DC Converter at Change in Load

DC converter at change in the load, is depicted in Figs. 7 (a-

b). The wind speed and insolation are kept at 7 m/s and 700 W/m², respectively. Initially a 3phase balanced load of 2.5 kW is connected at PCC. The DG is delivering 4.84 kW (shown in Fig.

7 (b)), which corresponds to the battery bank voltage of

125 V. Moreover, the DFIG and solar PV array powers are 2.013 kW and 4.122 kW, respectively as depicted in Fig.

7 (b). Since the total generation is more than the local demand, the remaining power goes to BES through a bidirectional buck/boost DC-DC converter as shown in Fig. 7 (a). At $t = 3$

s, an additional load of 2 kW is connected and again it is disconnected at $t = 5.5$

$$a_h(f) = 1/(1 + e^{-f})$$

s. During this period, it is observed that the power generation from all sources, remains unchanged and the increased load power is met by the BES through LSC. There is a minor sag and swell of DC link voltage, however, the solar MPPT is unaffected as seen from P_{sol} waveform. Moreover, the system voltage and frequency are maintained constant, as depicted in Fig. 7 (b).

B. System Performance at Variable Wind Speeds

The performance of the system at variable wind speeds are depicted in Figs. 8 (a-c). In this, a 3phase load of

4 kW is connected at PCC and the insolation is kept at 700 W/m². The DG delivers power of 5.67 kW based

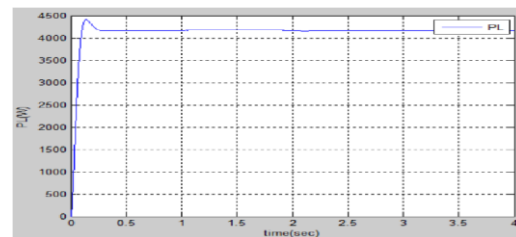
on the state of the BES, as depicted in Fig.

8 (b). The pattern of wind speed variation is depicted in Fig.

8 (a). It is observed that the controller regulates the DFIG rotor speed as per wind MPPT algorithm, as depicted in Fig.

8 (a). Moreover, it is observed that the DC link voltage is regulated. The system dynamic response during the transition of DFIG speed from super synchronous to sub synchronous speed region, is depicted in Fig.

8 (c). It is observed that wind MPPT is obtained d



10. However, both voltages and currents of DFIG and DG, are maintained balanced and follow the IEEE

519 standard. The LSC helps in unbalance and harmonics compensation of the connected load at PCC. The LSC currents and neutral current, are also shown in Fig.

10. Moreover, the variation of power at unbalanced nonlinear load, is depicted in Fig. 11. Fig.

11 demonstrates waveforms of V_r , V_{dc} , I_b , P_{sol} , P_w , P_D , PL and $PLSC$. From these results, it is observed that the DC link voltage is regulated and moreover, solar PV and wind MPPT operation is unaffected. The decrease in load power goes to BES through LSC, which is evident from I_b , PL and $PLSC$ waveforms. Moreover, V_r is maintained at constant value.

(a)

uring the variation of wind speed. Moreover, the fr
equency rotor currents, is changed according to the speed of operation of DFIG.

C. System Performance at Variable Insolation

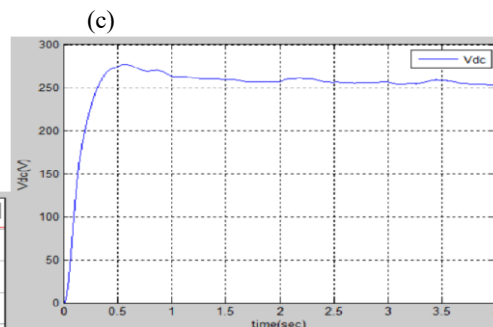
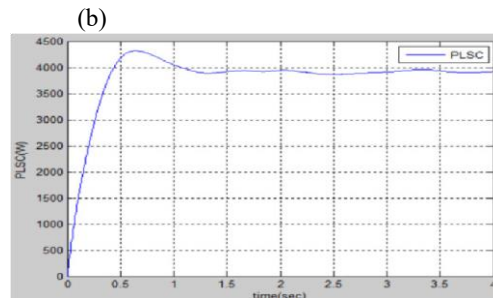
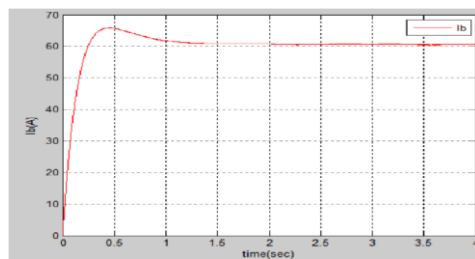
The performance of the system at varying solar radiation, is depicted in Figs. 9 (a-
b). In this, the wind speed is kept constant at 7 m/s. Moreover, the DG delivers
4.2 kW power based

on the battery voltage, as depicted in Fig.

9 (b). In this, a 3-
phase linear balanced load of nearly
4 kW is connected at PCC. The insolation of solar
PV array is varied from 700 W/m² to 800 W/m² at
 $t = 3$ s and again it is reduced to 600 W/m² at
 $t = 5.5$ s, as depicted in Fig.
9 (a). The DC link voltage is regulated by the bidi
rectional DC-
DC converter control for achieving the solar MPPT

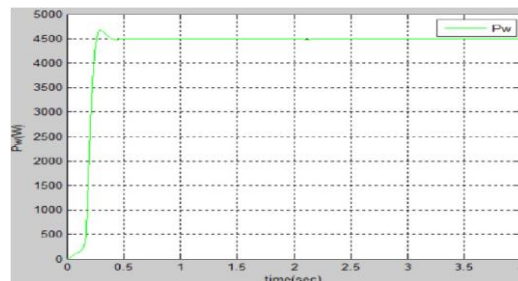
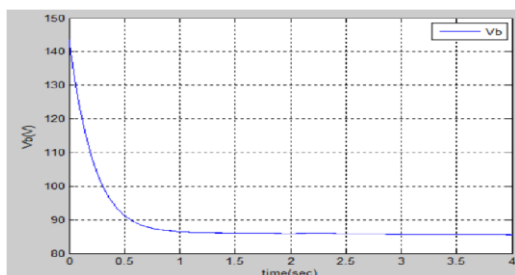
D. System Performance at Unbalanced Nonlinear Load

The dynamic performance of the system at unbalan
. Moreover, the solar MPPT is manifested by the P_{sol}
 waveform, as depicted in Fig. 9 (a).



ced nonlinear load, is depicted in Fig.

10. Initially, a balanced load of 6.7 kW is connected at PCC. It includes a linear lo
ad of
0.5 kW and remaining be the nonlinear load, conn
ected
on each phase. At $t = 2.6$
s, aphase of the load is disconnected and subsequently
phase-b, is also disconnected at $t = 2.8$
s, as depicted in Fig. (d)



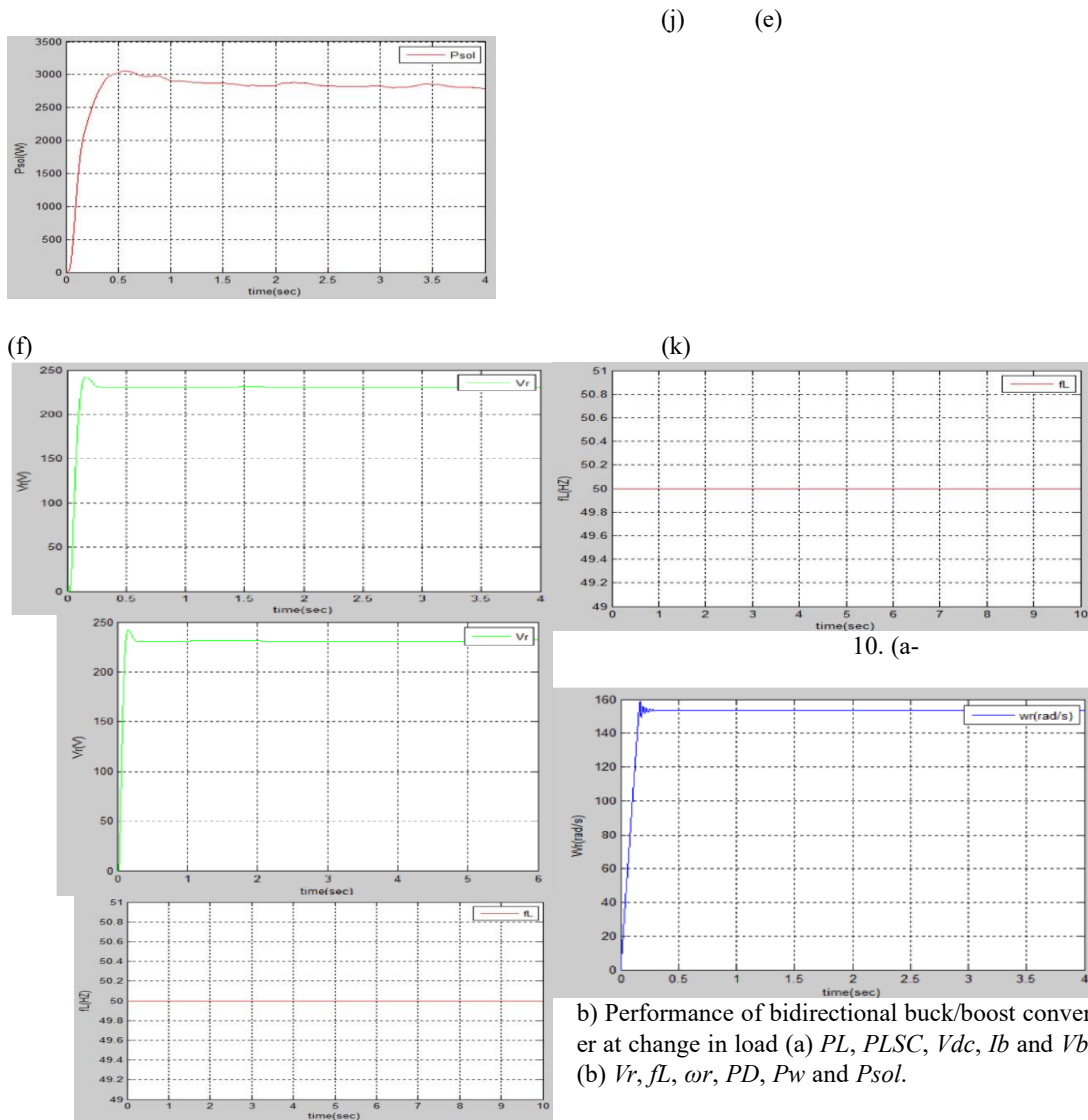


Fig.

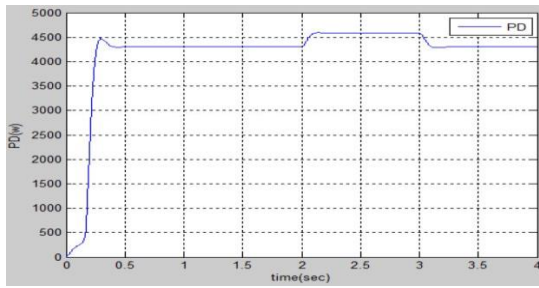
b) Performance of bidirectional buck/boost converter at change in load (a) PL , $PLSC$, V_{dc} , I_b and V_b (b) V_r , f_L , ω_r , PD , P_w and P_{sol} .

(g)

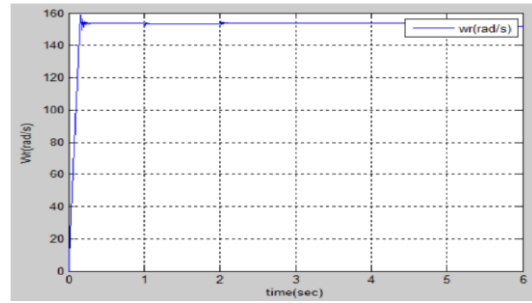
(a)

(h)

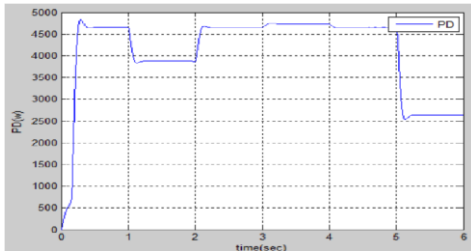
(b)

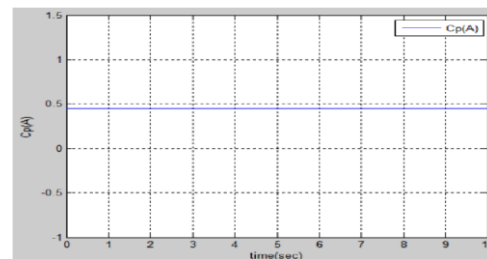
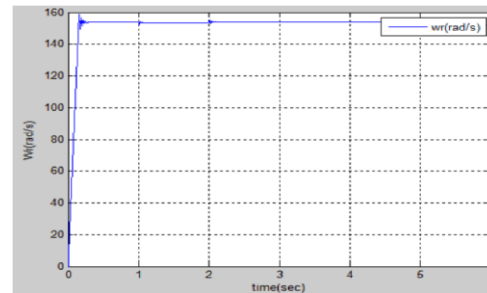
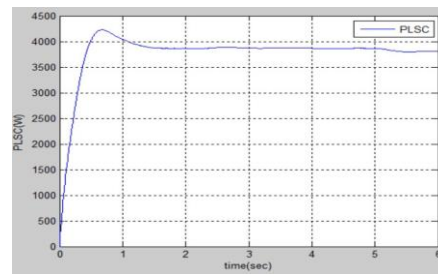
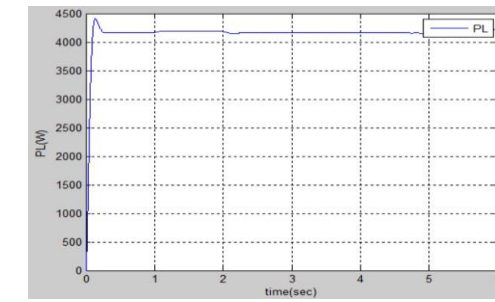
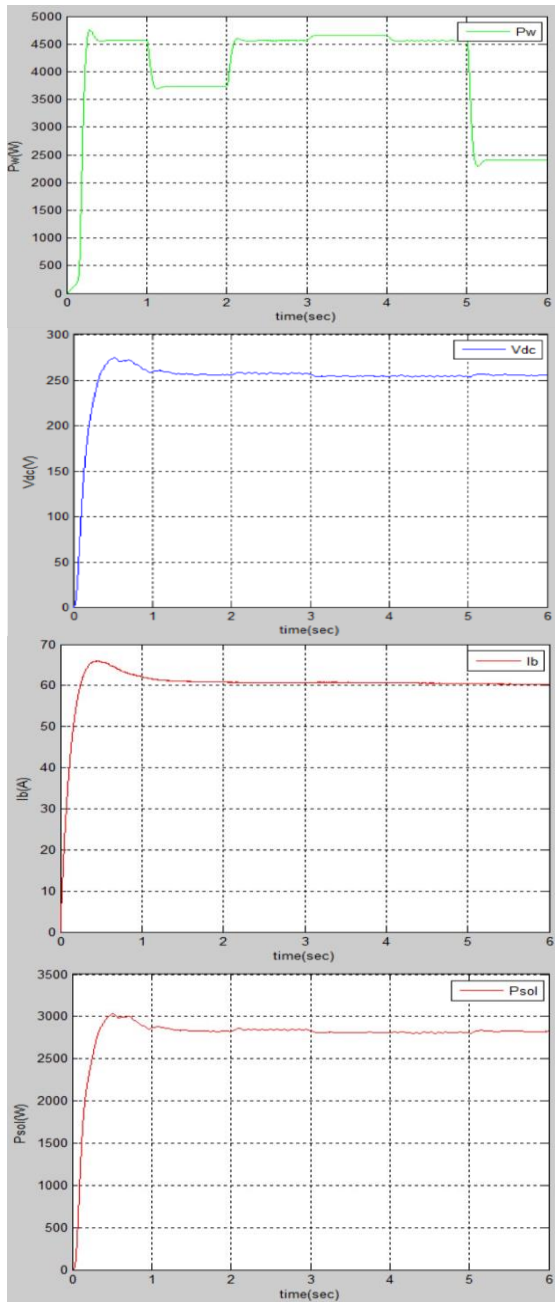


(i)



(c)





(i)

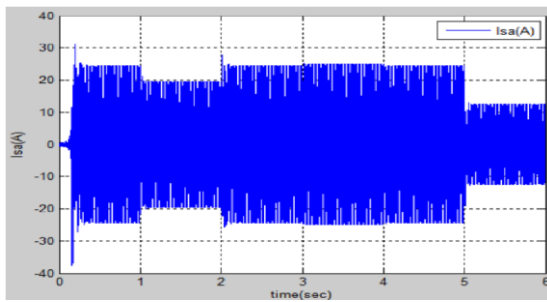
(e)

(j)

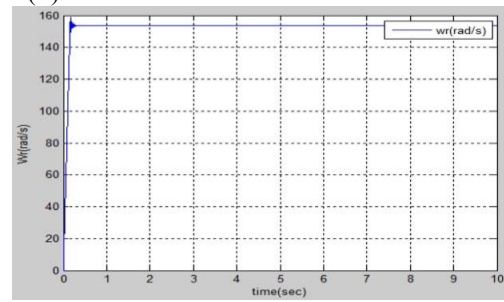
(f)

(k)

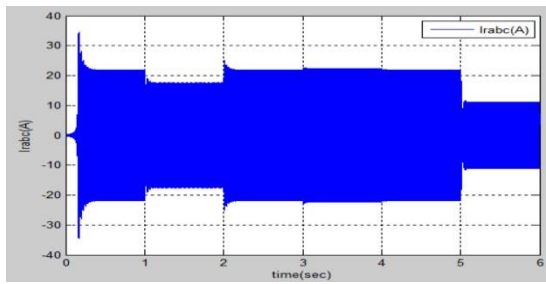
(g)



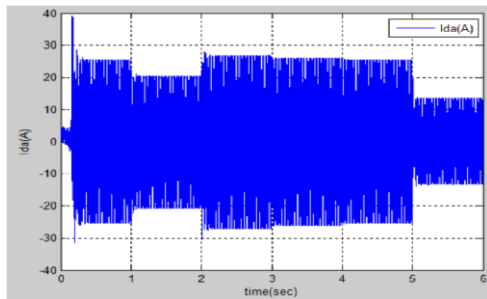
(L)



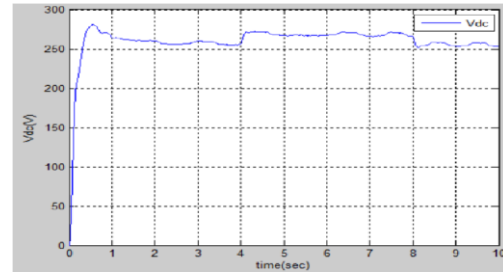
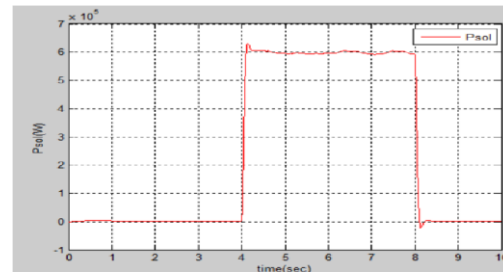
(b)



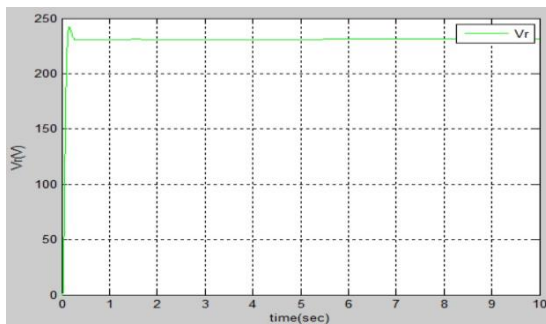
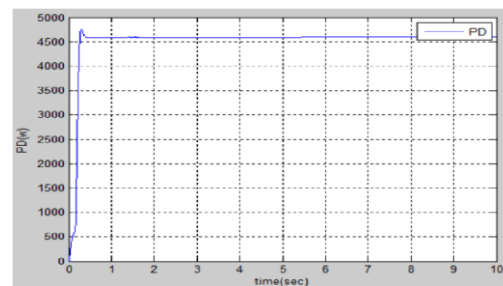
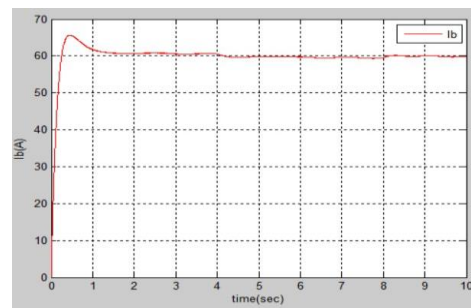
(m)



(n)



(c)



(d)

(o)

Fig.

11. System performance at variable wind speed (a) V_r , f_L , V_w , ω_r and P_w (b) V_{dc} , I_b , P_{sol} , P_D , P_L and $PLSC$. (c) system performance during changeover of DFIG speed from supersynchronous to subsynchronous speed region: V_w , ω_r , C_p , i_{sa} , i_{rabc} and i_{da} .

(e)

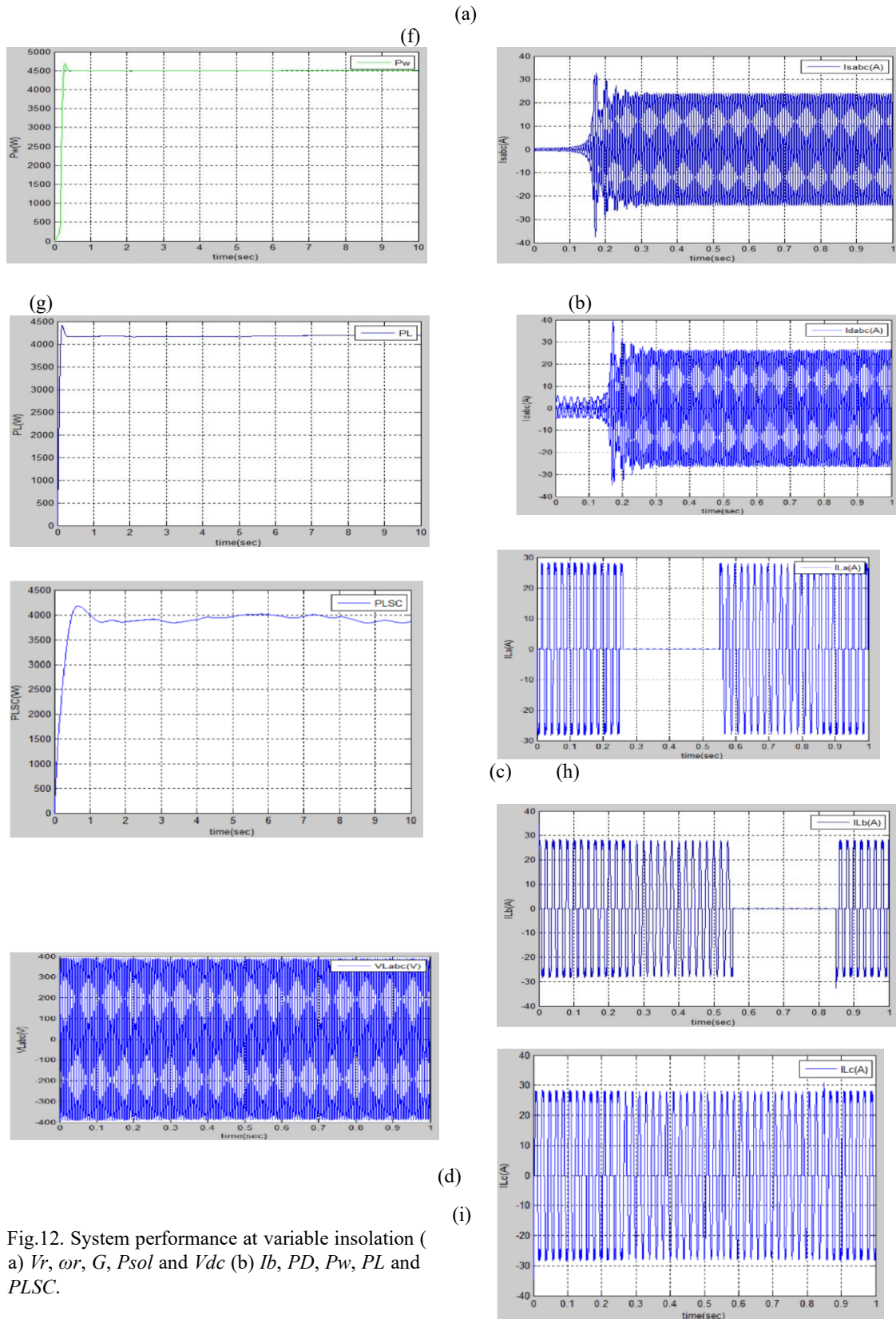
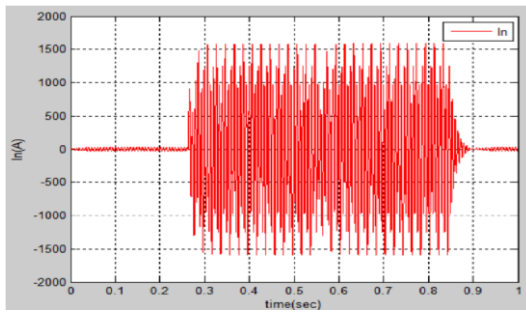


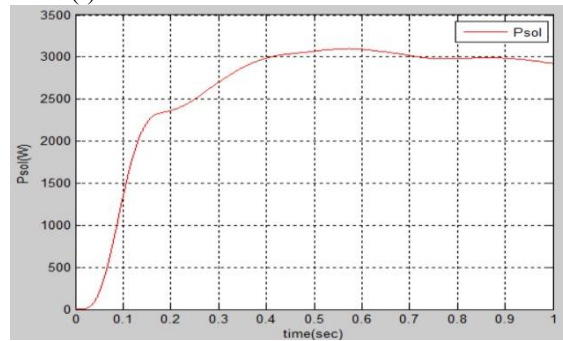
Fig.12. System performance at variable insolation (a) V_r , ω_r , G , P_{sol} and V_{dc} (b) I_b , P_D , P_w , P_L and P_{LSC} .

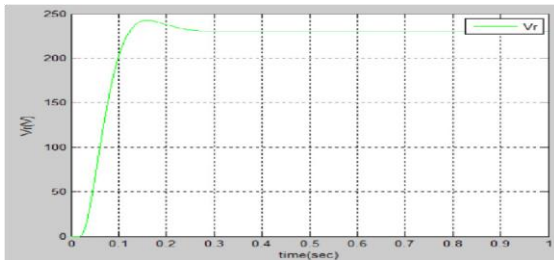
(e)

(a)

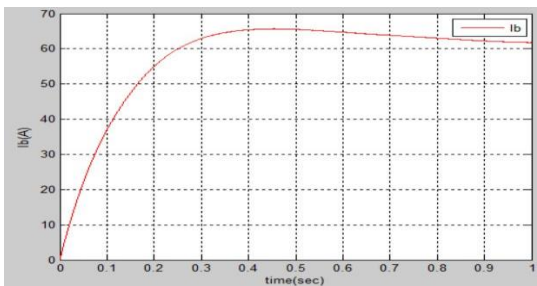
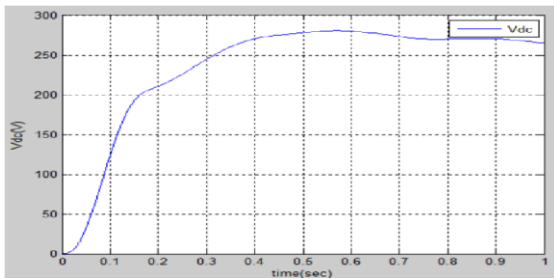


(f)



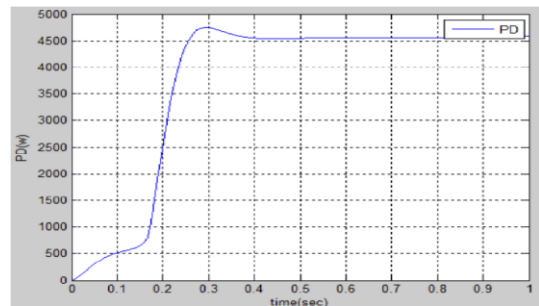
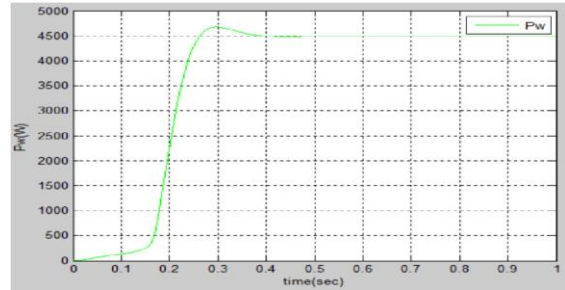


(h)

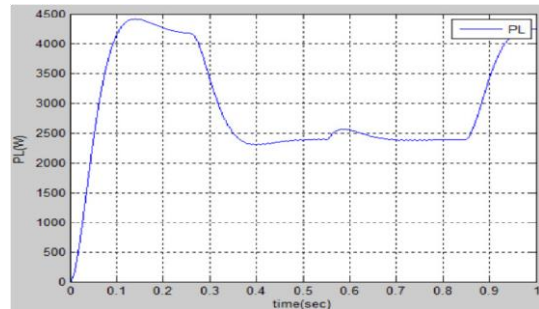


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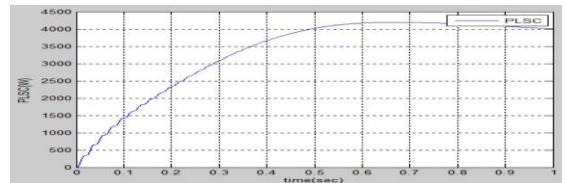
(j)



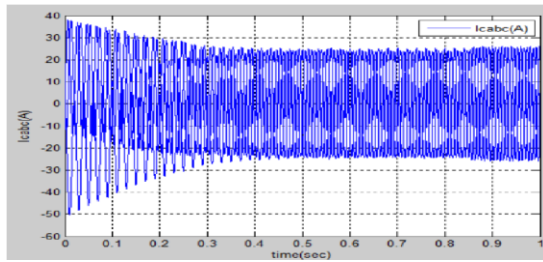
(m)



(i)



(m)



(g)

(L)

Fig.13. System performance at nonlinear unbalanced load: V_r , V_{dc} , I_b , P_{sol} , P_w , PD , PL and $PLSC$.

V. CONCLUSION

The proposed system has promising scope for islands, which are totally dependent on the dieselbased generation. The load regulation capability of

the diesel generator to operate in Efficient fuel zone reduces specific fuel consumption. The MPPT feature of proposed system in control, helps in maximizing generation and further helps to reduce the

cost of the energy. The system is also able to maintain phase currents balanced as well as and current harmonics within an acceptable limit for all types of

loads. The effectiveness of the system is demonstrated using simulated and test results and it is found

that the power quality is within acceptable limit under all practical scenarios.

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Pandla Vyshnavi was born in AP, India. Currently she is studying her M.Tech in Electrical & Electronics Engineering from Sri Padamavati Mahila University, Tirupathi, Andhrapradesh.



D. Himabindu is currently pursuing ph.D. in the department of EEE JNTUA university, Ananthapur and also working as an assistant professor-department of EEE in SOET, SPMVV, Tirupati AP, India. Her research interests include power electronics, electrical machines, & Modelling & Analysis of AC drives. She is a life member of 'ISTE'.