Grey Wolf Optimization based Power Management Strategy for Battery Storage of DFIG-WECS in Standalone Operating Mode

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Abstract: **This paper presents a novel grey wolf optimization based automatic power management strategy of a doubly fed induction generator (DFIG) - wind energy conversion system (WECS) operating in standalone mode. In isolated wind power generation system, either the dc-link or the ac load terminal is backed up by energy storage units, such as battery, super capacitor, dc power supply etc. In such cases, efficient power exchange from the supporting power source is very crucial during load fluctuation and intermittent wind speed. In this paper, a unique meta-heuristic algorithm known as grey wolf optimization (GWO) is introduced to ensure the optimized power exchange in a battery supported DFIG operating in standalone (SA) mode. The proposed optimization algorithm is chosen for its simplistic implementation, fast convergence and superior ability to avoid local optima over other conventional optimization techniques. The reference battery power is generated by the designed control unit which regulates the power flow in optimized manner through the bi-directional converter at battery end. Besides, the load-side and rotor-side converter control blocks are designed to stabilize the generated output. The simulation results of the overall system shows rigorous control over output voltage and load frequency under fluctuating wind speed and variable load condition and efficient battery power flow in standalone operating mode.**

Index Term- **Doubly Fed Induction Generator, Wind Energy System, Battery Power Management, Grey Wolf Optimization, Standalone mode.**

I. Nomenclature

$v_{ds}, v_{qs}, v_{dr}, v_{qr}, v_{dl}, v_{ql}, v_{db}, v_{qb}$—d-q axis stator, rotor, load and battery inverter end voltages (V)
$i_{ds}, i_{qs}, i_{dr}, i_{qr}, i_{dl}, i_{ql}, i_{db}, i_{qb}$— d-q axis stator, rotor and load, battery inverter end currents (A)
$\psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr}$ −d-q axis stator and rotor flux linkages (wb).
R_s, R_r— stator and rotor winding resistances (Ω)
ω_s, ω_r—synchronous and rotor angular speed (rad/s)
p —derivative operator *(p = d/dt).*
P—Number of pole pairs
$L_s = L_{ls} + L_m$ —Stator self-inductance (H)
$L_r = L_{lr} + L_m$ —Rotor self-inductance (H)
L_{ls}, L_{lr}— Stator and rotor leakage inductances (H)
L_m— Magnetizing inductance (H)
L_b—Inductance of battery filter (H)
R_b—Resistance of battery filter (Ω)
T_e −Electromagnetic developed torque (N-m)
V_t^* −Reference voltage at load end (V).
V_{dc} − dc-link voltage(V).
V_{act} −Actual voltage at load end (V).
P_{bat} −Power at the battery terminal (W).
V_t^* −Reference voltage at load end (V).
P_{load}- Power consumed by load (W).
T_{tur}^* −Reference turbine torque (Nm).

II. Introduction

Recently, wind energy has become one of the most promising and economically viable renewable energy sources all over the world. In wind power systems, DFIG is preferred over other power generators as it is less expensive and can operate over a wide speed range. DFIG also provides the advantages of reduced flicker and four-quadrant active and reactive power control. It also facilitates the use of low-power converters in grid-side and rotor-side and decoupled control of real and reactive power [1]. In a flexible power network, DFIG can either be standalone or grid connected. The stand-alone mode is required where the grid voltage is not available such as remote area or in case of grid-power failure when the DFIG has to fulfill emergency power demand of local loads. In this mode of operation, the machine is equipped with power electronics interfaces to regulate voltage and frequency at the load end. One of main challenges of islanding operation of DFIG based WECS is to regulate the autonomous frequency of the generation system. Unlike grid-connected system where the frequency is determined by the grid voltage, the DFIG confronts the loss of frequency reference from the supply grid. Furthermore, voltage regulation and speed limit of wind turbine are the two other concerns related with the standalone operation of DFIG-WECS. Therefore, this paper suggests a PI based rotor side converter control algorithm to regulate the frequency and the output voltage of the DFIG based WECS operating in islanding mode under varying wind speed condition.

On the other hand, due to the intermittent nature of wind flow, the wind generator can't sustain its operation without the support of additional power sources. Auxiliary energy sources such as internal combustion engine, photovoltaic panels are often integrated into the system to provide appropriate performance [2]. Especially in wind driven power system operating at standalone mode, supporting energy storage system increases the power quality of the generation unit [3,4]. Energy management could play a vital role to

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guarantee the efficacy and stability of the autonomous operation of DFIG operated WECS in both energy surplus and energy deficit conditions. Power optimization in auxiliary supply is vital for the longevity of storage supply lifespan and to achieve better efficiency. So far, the researchers have mainly investigated the modeling and control features of energy storage units for grid connected wind power generation systems [5,6]. A hybrid energy storage system utilizing a super-capacitor and a battery coupled with the generator is studied in [7] for wind power smoothing. The study is conducted on real-time simulator for grid-connected environment. On the contrary, very few researches have been conducted on the storage power optimization of standalone wind power system. An energy management algorithm has been proposed in [8] using battery storage and super-capacitor with a view to ensure safer operation of the battery storage system by avoiding the operation at lower depth of discharge. However the algorithm lacks robustness as the method requires the separation of low and high frequency power component of the demand generation mismatch. An energy storage converter control system has been developed in [9] for energy management of the storage unit during deficit of mechanical energy on the shaft. The controller is dependent on many threshold values which make it inflexible under varying conditions. Although intelligent control techniques may provide outstanding control features with rigorous convergence characteristics under promptly varying conditions, until now, only a handful of significant attempts have been made for energy optimization in WECS by adopting intelligent stochastic algorithm such as genetic algorithm, particle swarm optimization, artificial bee colony algorithm, grey wolf optimization etc. Among these techniques, grey wolf optimization is a meta-heuristic robust optimization technique which is inspired by the hunting method of Grey wolves [10]. Compared to the other stochastic optimization techniques, GWO method provides the ability to avoid local optima, easier implementation with few parameters to adjust [11, 12]. In wind power application, the maximum power tracking with the utilization of grouped grey wolf optimizer [13] and optimal blade pitch control via GWO-PID controller [14] are few of the significant works done by researchers that utilizes the grey wolf optimization technique. Still the controllers are applied in grid-connected DFIG system. Standalone operation has not been considered in those works. Therefore, a novel control strategy has been developed in this paper that optimizes the power of the auxiliary power source of DFIG operating in standalone mode. In the proposed configuration, battery storage is utilized as the storage unit because of its high energy density. The proposed algorithm is based on grey wolf optimization technique that can successfully measure the optimum reference power for the power control block and thus ensures maximum power extraction from the turbine with optimized energy usage from battery source. In addition, a PI controller based converter control scheme is designed for standalone operation mode of DFIG-WECS to regulate the output frequency and the terminal voltage to a specified value. The overall control scheme improves the effective of the supporting energy source

III. Proposed DFIG-WECS Configurations

In islanding mode of DFIG based WECS, back-to-back converters are connected at the rotor side and the load side, which can be controlled independently. The dynamic model of DFIG can be obtained from d-q axis voltage equations in synchronous rotating reference frame as shown in (1)-(4). The d-q transformation of three phase ac quantities eliminates the effect of time varying inductances.

$$v_{ds} = R_s i_{ds} + p\psi_{ds} - \omega_s\psi_{qs} \tag{1}$$
$$v_{qs} = R_r i_{dr} + p\psi_{qs} + \omega_s\psi_{ds} \tag{2}$$
$$v_{dr} = R_r i_{dr} + p\psi_{dr} - (\omega_s - \omega_r)\psi_{qr} \tag{3}$$
$$v_{qr} = R_r i_{qr} + p\psi_{qr} + (\omega_s - \omega_r)\psi_{dr} \tag{4}$$

The motion equation, which describes the dynamic behavior of the DFIG rotor mechanical speed in terms of mechanical and electromagnetic torque can be expressed as,

$$\frac{d\omega_r}{dt} = \frac{P}{J}(T_e - T_m)$$
$$= \frac{P}{J}\{\frac{3PL_m}{2(L_sL_r - L_m^2)}(\psi_{dr}\psi_{qs} - \psi_{ds}\psi_{qr}) - T_m\} \tag{5}$$

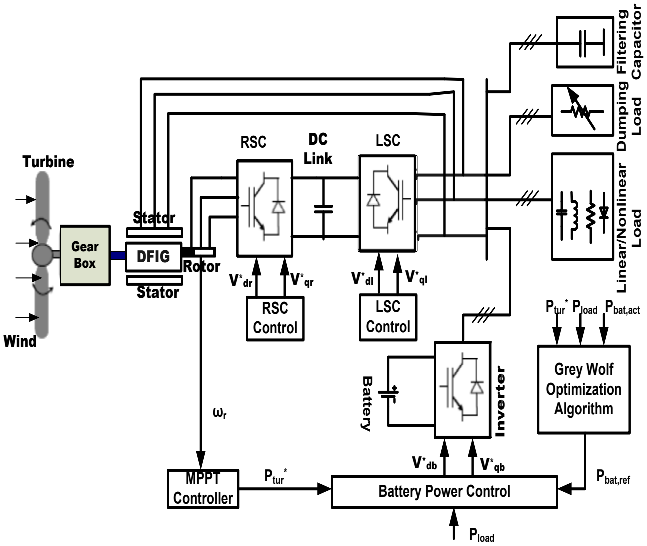

Fig. 1. Overall configuration of the WECS showing the operational blocks at standalone mode incorporating battery storage power management.

One of the unique features of DFIG is that it has not necessarily to be magnetized from the stator end, it can be magnetized from the rotor circuit too. In standalone mode of operation for DFIG based WECS, the rotor side converter (RSC) ensures the power supply to the consumers at constant amplitude and frequency by controlling the rotor current components while the load side converter (LSC) is required to maintain the dc link voltage and reactive power control at the stator end of the generator. Although the typical implementation of DFIG are found in grid-connected system for wind power applications, in case of power outage of the main grid, the local power source needs to take over the control of islanded loads. In such cases, the generator should have enough capacity to supply power to local base load. For a standalone application of WECS, the power capacity of auxiliary storage unit is crucial to handle power variations from the involved wind energy source. DFIG can successfully function in isolated mode if supporting energy sources such as battery, fuel cells, internal combustion engine or long term energy storage are connected to the DC or AC side. In Fig. 1, the standalone mode of operation is shown for DFIG based WECS with a battery storage connected at the load end.

TABLE I: WIND TURBINE, DFIG AND LOAD PARAMETERS

Parameters	Value
Rated turbine power	2 MW
Pitch angle	0˚
Blade radius	42 m
Rated generator power	2.5 MW
Rated slip	-0.1667
Rated frequency	60 Hz
Number of pole pairs	2
Leakage resistance	2.9 mΩ
Leakage inductance	0.08 mH
Magnetizing inductance	2.5 mH
dc bus capacitance	0.3 F
Load frequency	60 Hz
Rated load voltage (rms)	750 V
Battery storage rating	100 kWh
Dump load rated Power	500 kW
Maximum battery current	1000 Amp

An indirect maximum power point tracking control block is implemented in the design that can generate the reference torque for the DFIG. It also provides optimum turbine power for the GWO coding block. The GWO algorithm implementation block provides the reference battery power ($P_{ref,bat}$) to optimize the power generation and absorption in the battery supply. The battery control block provides the control pulses for the inverter connected to the battery supply. The dumping load absorbs excessive power when the turbine power exceeds the combined limit of the load demand and maximum battery power. Besides, filtering capacitors are connected to the stator of the DFIG to suppress the high-frequency harmonics from the supply. Table 1 shows the specification of the wind turbine, DFIG and load parameters that have been utilized in simulation.

IV. DESCRIPTION OF THE CONTROL OPERATION

Intermittent wind speed and variable load power demand make the operation of wind-based power systems challenging in a standalone environment. The implementation of GWO algorithm based power management for isolated operation of DFIG is suggested in this work for improved control and efficient energy management. The following subsections illustrate the structure of load and rotor side converter scheme along with and detail analysis of GWO method based battery power control for the overall system.

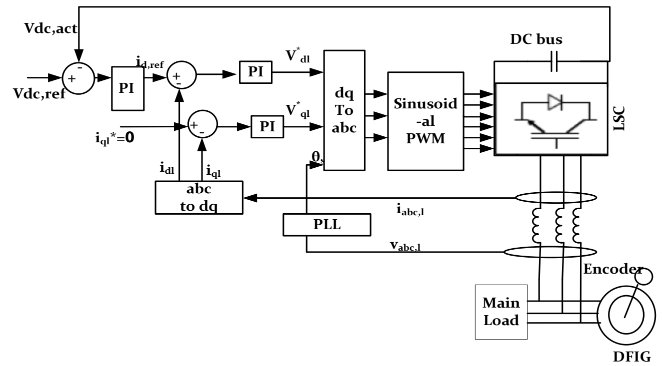

Fig. 2. LSC control for SA operating mode of DFIG.

A. LSC Control Operation

The load side converter maintains the dc-link voltage constant irrespective of the value and direction of the power flow. It is also possible to control the flow of reactive power by GSC. However, in this paper, for simplification of the designed scheme, PI controller based configuration is implemented in GSC control as depicted in Fig. 2. The reference q-axis load current component (i_{ql}^*) is considered as zero to nullify the reactive power provision through the LSC.

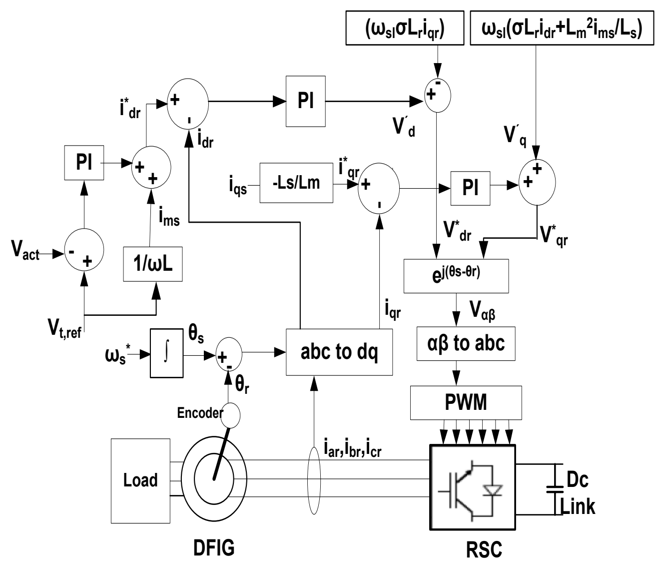

Fig. 3. RSC control for SA operating mode of DFIG.

B. RSC Control Operation

In SA mode, the control complexity lies in the fact that stable grid voltages are not available. The output voltage and frequency needs to be controlled by the converters. The RSC is designed as current controlled voltage source inverter to serve the load voltage and frequency control purpose as shown in Fig. 3.The reference phase to phase voltage for the load is selected as 1200 volt whereas the stator flux position (θ_s) is derived from a free running integral of the stator frequency demand ω_s* (60 Hz).

$$\theta_s = \int \omega_s^* dt \tag{6}$$

Typically, in autonomous operation of DFIG, the rotor side fully contributes to the magnetizing current component. With indirect orientation scheme, i_{qr} can no longer be used to control the generator torque; this is entirely appropriate for the stand-alone application in which the turbine power, load demand and battery supply effectively determines the torque for a given shaft speed. The stator flux is controlled using the q-axis current i_{ql}. The reference q-axis rotor current i_{qr} is controlled according to (7).

$$i_{qr}^{*} = -\frac{L_s}{L_m} i_{ql} \tag{7}$$

This current equation forces the orientation of the reference frame along the stator flux vector position. The rotor d-axis current i_{dr} has two components: the magnetizing current $i_{dr,m}$ and load demand current $i_{dr,l.}$ The current component $i_{dr,m}$ fulfills the no-load reactive power demand of DFIG and $i_{dr,l}$ contributes to the load reactive power requirements [8]. The reference current of $i_{dr,l}^{*}$ can be achieved by compensating the terminal voltage error through PI controller as shown in (8) and the no-load reactive power current component $i_{dr,m}$ can be obtained by utilizing (9).The overall d-axis rotor reference current is summation of the two components as shown in (10).

$$i_{dr,l}{}^{*} = \left(k_p + k_i s\right)\left(V_{t,ref} - V_{act}\right) \tag{8}$$

$$i_{dr,m} = \frac{V_{act}}{\omega L_m} \tag{9}$$

$$i_{dr}^{*} = i_{dr,l}^{*} + i_{dr,m} \tag{10}$$

The roportional and integral constants for the PI control blocks utilized in LSC and RSC control are determined by internal model control tuning method[15].

C. Grey Wolf Optimization (GWO)

In this section the inspiration of the proposed method is first discussed and the mathematical model is provided later.

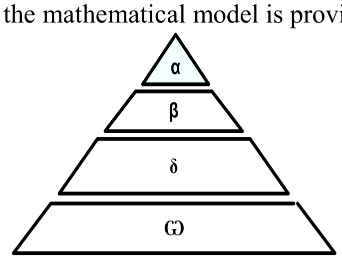

Fig. 4. Hierarchy of grey wolf optimization technique.

C.1 Inspiration

Grey wolves (Canis lupus) are predators that mostly prefer to live and hunt in groups. The interesting fact of these animals is that they maintain strict social dominant hierarchy as shown in Fig. 4. The top member in the hierarchy is the alpha (α) wolf and the subsequent ranks are assigned for beta(β), delta(δ) and omega(Ꞷ) wolves. The Ꞷ wolves keep exploring in arbitrary domain to improve the global optimization while the α,β,δ guide them towards the fittest position. For mathematical model, it is considered that the alpha provides the fittest solution while beta and delta are in second and third best position respectively.

C.2 Encircling Pattern

The prey encircling of grey wolves can be modeled as follows [10]

$$\vec{N} = \left|\vec{M}.\vec{X_p}(j) - \vec{X}(j)\right| \tag{11}$$

$$\vec{X}(j+1) = \vec{X_p}(j) - \vec{R}.\vec{N} \tag{12}$$

Where j indicates the current iteration, $\vec{R} = 2\vec{k}.\vec{u}_1 - \vec{k}$, $\vec{M} = 2\vec{u}_2$, $\vec{X_p}$ is the current position of the prey, $\vec{X}$ is the current position vector of the wolf, the components of $\vec{k}$ linearly decreases from 2 to 0 and $\vec{u}_1, \vec{u}_2$ are random vectors in [0,1].

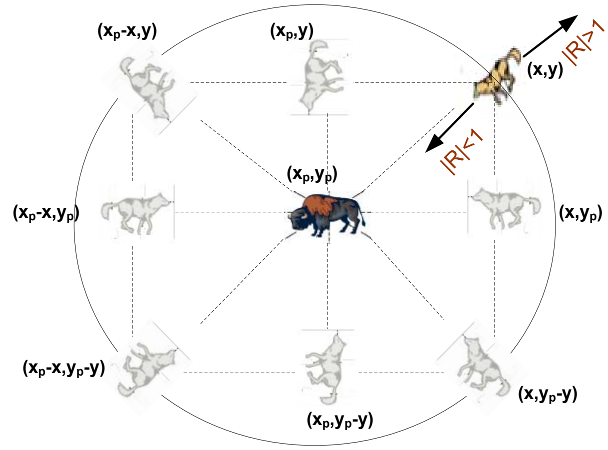

Fig. 5. Position update pattern of wolves using random vectors.

To illustrate (11) and (12) the position update of wolves is shown in Fig. 5 in a two-dimensional space. It is evident that a grey wolf in the position of (x, y) can update its position according to the position of the prey (x_p,y_p). The fittest position can be searched in random space by adjusting the vectors $\vec{M}$ and $\vec{R}$. For instance, a wolf can reach in position (x_p-x,y)can be reached by setting $\vec{M} = (1,1)$ and $\vec{R}$=(0,1).

C.3 Position Update Mechanism:

Grey wolves have the ability to recognize the location of prey and encircle them. Alpha leads the hunting and beta and delta are likely to follow the alpha. During optimization, the first three fittest solutions are obtained by these three entities. Other wolves are considered as Ꞷ and reposition themselves with respect to the position of α, β and δ. The following equations are utilized to the positions of the wolves in updating their positions.

$$\vec{N}_\alpha = \left|\vec{M_1}.\vec{X_\alpha} - \vec{X}\right| \tag{13}$$

$$\vec{N}_\beta = \left|\vec{M_2}.\vec{X_\beta} - \vec{X}\right| \tag{14}$$

$$\vec{N}_\delta = \left|\vec{M_3}.\vec{X_\delta} - \vec{X}\right| \tag{15}$$

Where, $\vec{X_\alpha}$ is the position of alpha, $\vec{X_\beta}$ is the position of beta, $\vec{X_\delta}$ is the position of delta and $\vec{X}$ indicates the current position of the solution. $\vec{M_1}, \vec{M_2}, \vec{M_3}$ are random vectors. Equations (13)-(15) calculate the distance between current solution and alpha, beta and delta respectively. The final position can be calculated by utilizing the following equations.

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{R_1}.\overrightarrow{N_\alpha} \quad (16)$$

$$\overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{R_2}.\overrightarrow{N_\beta} \quad (17)$$

$$\overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{R_3}.\overrightarrow{N_\delta} \quad (18)$$

$$\vec{X}(j+1) = \frac{\overrightarrow{X_1}+\overrightarrow{X_2}+\overrightarrow{X_3}}{3} \quad (19)$$

Here, $\overrightarrow{R_1}, \overrightarrow{R_2}, \overrightarrow{R_3}$ are random vectors and j is the number of iterations.

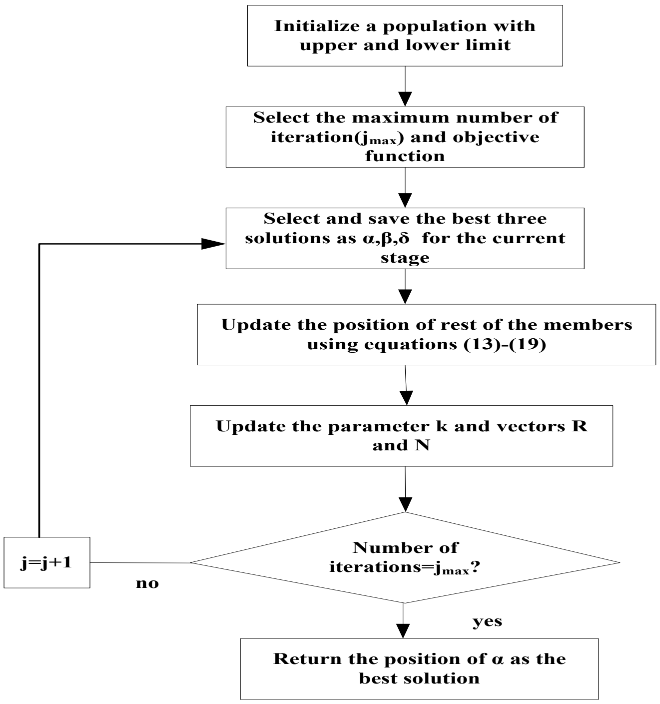

Fig. 6. Flow chart of GWO technique.

It is worthy to mention here that the vectors $\vec{R}$ and $\vec{N}$ are random and adaptive and these two vectors provides the exploration for the GWO algorithm. The exploration mechanism is activated when $\vec{R}$ is greater than 1 or less than -1. The vector $\vec{N}$ also defines exploration if it has a value greater than 1.Oppositely, the exploitation is executed when $|R|<1$ and $N<1$ as shown in Fig. 5. In coding scheme, R is decreased linearly during optimization in order to emphasize exploitation as the iteration counter increases. However, *N* is generated arbitrarily throughout optimization to ensure exploration or exploitation at any stage. The flow chart in Fig. 6 illustrates the general steps of the GWO algorithm.

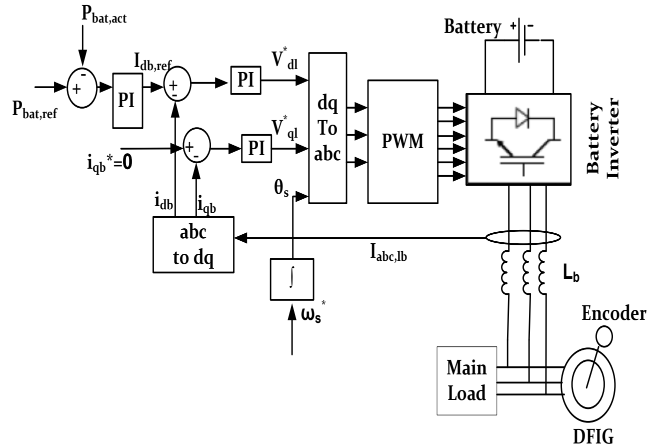

Fig.7. Battery Power control for bidirectional converter.

D. Power Management Strategy for Battery Storage

The battery storage system in the proposed system is connected with the DFIG via power converter and filter components. The bidirectional power converter regulates the power flow from and towards the battery which is controlled by the battery control block as shown in Fig. 7. The main purpose of the battery power control unit is to provide additional amount of energy to the load unit during energy deficit from the DFIG and to maintain reverse for battery-charging in case the generation exceeds the load demand.

The GWO technique is utilized to obtain the reference battery power for the inverter control unit. The GWO block collects the actual battery power ($P_{bat,act}$), demand load power (P_{load}) and generator power as the input and generates the optimum power reference signal for the storage power control block by utilizing the following objective function,

$$f_{ob} = (P_{load} - T_{tur}^{*}\omega_r - P_{bat,act})^2 \quad (20)$$

An indirect MPPT control algorithm is used to generate the reference turbine torque which is provided as the input torque of the DFIG. Thus the objective function aims to achieve the optimized battery power reference by extracting maximum power from the turbine. For GWO coding scheme, the maximum and minimum power limit of the search space is set as $P_{bat,max}$ and $-P_{bat,max}$ respectively. The maximum number of iteration is set as 500.After each iteration the error calculated by the objective function is stored while the best three solutions of battery reference power is saved as α,β and δ. The other members in the search space are updated concurrently by modifying random vectors R and N. After attaining maximum iteration, the final value of α is returned as the optimized reference value for battery power. The steps are repeated for each time sample of the simulation.

The battery reference power generated from GWO implementation block is provided to the inverter control unit. The proposed control utilizes the equations shown in (21)-(25) to achieve the desired output.

$$i_{bat,ref} = (P_{bat,ref} - P_{bat,act})(k_{pb} + \frac{k_{ib}}{s}) \quad (21)$$

$$v_{db}^{*} = v_{db} - v_{db,l} - L_b\omega i_{qb} \quad (22)$$

$$v_{qb}^{*} = v_{qb} - v_{qb,l} + L_b \omega i_{db} \quad (23)$$

$$v_{db,l} = R_b i_{db} + L_b \frac{di_{db}}{dt} \quad (24)$$

$$v_{qb,l} = R_b i_{qb} + L_b \frac{di_{qb}}{dt} \quad (25)$$

E. Dumping Power Control

When battery storage reaches to its maximum capacity of storage, the dump load control is activated to absorb the excessive energy. The exact nature of the dump load depends on the application of standalone system. Space heating via resistive load or water pumping for irrigation can be two possible options [16]. The required condition for activation of the dumping power load is given in (26).

$$P_{dump} = \begin{cases} x, when\ x = P_{tur} + P_{bat,max} - P_{load} > 0 \\ 0, when\ x < 0 \end{cases} \quad (26)$$

V. Simulation Results

In this paper, the efficacy of the GWO algorithm based battery storage power control strategy has been observed for Standalone DFIG-WECS. The simulation of the proposed system is done under different operating conditions such as, variable wind speed and load changing conditions. Sample results are presented below.

In Fig. 8, the performance of the load side and rotor side converter is illustrated while wind speed undergoes though a rapid variation within the range of 7 ms^{-1} to 10 ms^{-1}(Fig. 8(a)). It can be observed that the load side converter maintains the dc-link voltage to the required reference level (Fig. 8(b)) while the rotor side converter manages the output frequency stays around the reference value of 60 Hz with slight fluctuation (Fig. 8(c)). The terminal voltage at the load shows picks and valleys around its desired level (750 volt) with the variation of turbine torque (Fig. 8(d)) using variable wind speed condition. The combination of torque variation, battery voltage ripple and dc bus voltage fluctuation causes the deviation of the terminal voltage from the steady level. Figure 9 shows the system performance under variation of load demand. The mismatch in between the generation and the load causes deviation in the load frequency and terminal voltage as depicted in Fig. 9(b) and 9(c). However the variation is found within the acceptable limit.

The proposed power management scheme ensures instant power control of the battery unit and dumping load. The turbine power is varied while the load power is kept constant for the analysis (Fig. 10(a,b)). It is clearly seen from Fig. 10(c) that the battery keeps power transfer until turbine power exceeds the load power. Fig. 10(d) depicts that the damping load starts extracting power as soon as the battery power reaches to its maximum limit where $P_{b,max}$=1 MW . Fig. 10(e) shows the corresponding alternation of battery current for the existing situation. The analysis proves the effectiveness of the proposed power management scheme in standalone DFIG based WECS where the battery power control unit successfully manages the power allocation among the units.

The effectiveness of the grey wolf optimization algorithm coding block is tested under different conditions. The algorithm provides excellent performance with steep convergence. Figure 11 illustrates the performance of the GWO control under turbine torque varying condition. The output of the GWO implementation generates the reference battery power which merges with the actual power produced by battery unit. For better illustration the power signals are filtered with low-pass filter block (Fig. 11(a)). The convergence curve for the objective function is shown in fig. 11(b). The outcome of the objective function is plotted against the number of iterations obtained for the duration of one sampling period. The y-axis data is plotted in logarithmic scale for proper visualization. Even though GWO algorithm starts the process in an abstract search space without having any idea about the location of the optimum, it can return the fittest solution very promptly. The fleeting characteristics of the convergence curve and the avoidance of local optima during the solution steps proves the efficacy of the algorithm.

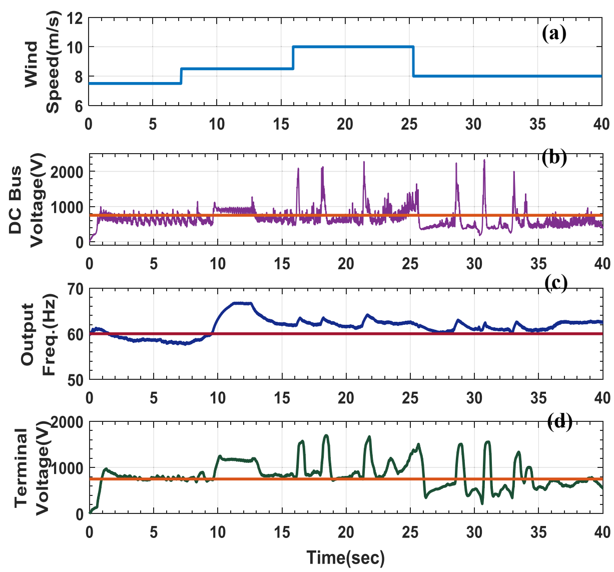

Fig. 8. LSC and RSC controller performance in the proposed standalone DFIG for wind speed variation: (a) Fluctuation in wind speed, (b) Variation in dc-bus voltage, (c) Corresponding change in output load frequency, (d) Alternation in terminal voltage at load end.

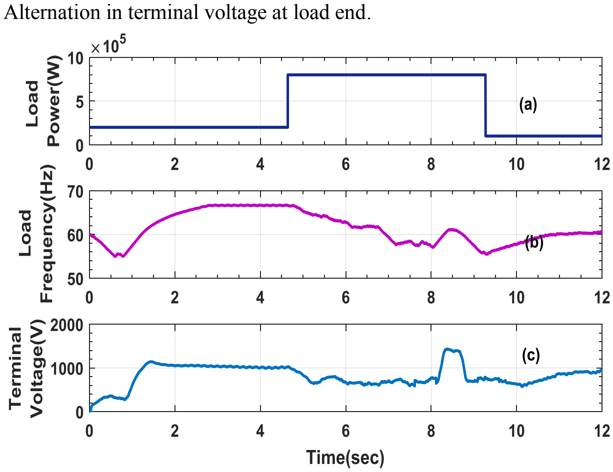

Fig. 9. Controller performance in the proposed standalone DFIG under variation in demand load power: (a)Variation of power demand at load end , (b) Corresponding change in output load frequency, (c) Terminal voltage at load end.

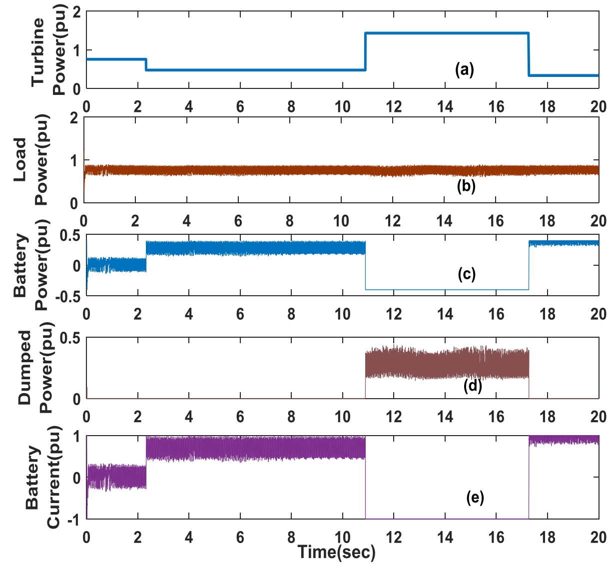

Fig. 10. Performance of the GWO algorithm based power control unit: (a) Variation in turbine power (pu), (b) Load power (pu), (c) Power contribution from battery (pu) (d) Corresponding sequence in dumping load power(pu), (e) Battery current variation (pu).

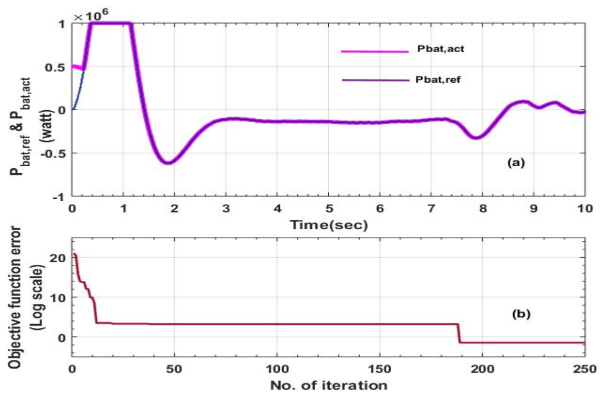

Fig. 11. Performance of the GWO algorithm: (a) Reference and actual battery power, and, (b) convergence curve for the objective function.

VI. CONCLUSION

A novel grey wolf optimization based power management algorithm for isolated-DFIG based WECS has been presented in this paper. The performance of the proposed control system has been investigated for isolated load under dynamic operating conditions such as variable wind speed, variable load conditions, etc. The GWO algorithm effectively generates the power reference for the inverter control of the battery source. The convergence speed and ability to avoid of local optima in random search space suggests the superiority and robustness of the of the proposed optimization technique. The optimized objective function guarantees the efficient energy flow to and from the battery end while the energy management system ensures the enhanced efficiency and longevity of battery storage with the utilization of rigorous power control and dumping load management. Besides, the PI controller based RSC and GSC control blocks are capable of maintaining constant voltage and frequency at the load end during abrupt variation of the load power demand and wind speed. The simulation results suggest that the designed control system shows satisfactory performance by coordinating the power flow between the system components along with proper regulation of voltage and frequency at the AC side.

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