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Improving Performance of Solar Array Fed BLDC Drive Using Firefly Algorithm Based High Gain Converter

Abstract: The improved transient response of PID controller for improved Luo converter supplied Brushless DC (BLDC) motor using solar energy source is extensively investigated. The BLDC drive uses a hybrid PV system and battery-based power generation as a power source to assure continuous power supply to pump water regardless of solar insolation. The PV system serves as the main energy source, and the battery providing as a backup source that discharged its power only during inclement weather or at night if the photovoltaic panel is insufficient to operate the centrifugal pump. The solar panel feeds power into the battery, whenever water to the field is not required, thus there is no need for an extra power source to charge the batteries. The high output voltage gain DC-DC converter does not make any discomfit to the system performance in regards to irradiance variation, switching loss, or power loss by converter or motor side respectively. Moreover, current sensor, voltage sensor, and control circuits are completed excluded which enhance performance and the cost of the system get reduced effectively. A bidirectional charging control allows a bi-directional converter to alter the battery operation mode automatically. The overall system performance is validated using simulation and experimental setup.

Keywords: Evolutionary Algorithm, Renewable Energy, DC-DC converters, Optimization technique, PID controller, system control.

I. INTRODUCTION

Due to cost reduction power converters increasing the rate of production in a wide range of applications for the past few years. To satisfy the energy demands usage of fossil fuel drastically increased for various applications which emerge to invite the use of alternate energy resources. Among various energy resources [1], solar has become very popular and has many advantages over other sources like portability, long life span, etc. The output response from the PV panel is unsteady and not enough to fulfil the reasonable requirement because its outcome is completely dependent on irradiation level and temperature of sunlight [2]. The intermediate section of solar and BLDC drive via VSI is completely accomplished by DC-DC converters. Various classical converters topologies like a buck, boost, and buck-boost converter, where transfer gain ratio of voltage gets restricted by increasing the duty cycle ratio cause switching stress on semiconductor devices and power diodes. Nowadays, the voltage lift technique [3] - [4] is successfully employed in DC-DC converters to get high voltage gain with less parasitic components. In addition to that, it also has a lot of advantages over basic converters like low output ripple current, small in size, no inrush current, and high-power density [5] - [6]. In this work, Positive Output self-lift Luo converter plays a vital role in energy conversion from low and non-linear nature of solar input voltage into high and linear output voltage respectively. The non-linear nature output from the solar panel further affects the dynamic performance of the converter. Hence, for a better result from the converter side, efficient closed-loop control methods are implemented.

Many control techniques are utilized for several converters such as PID, pole placement, LQR method, etc. [7]- [9] which are now used along with optimization techniques to enhance the system performance. Various optimization algorithms are discussed in several kinds of literature [10]- [13] like genetic, particle swarm optimization, cuckoo search, fireflies, etc. is introduced based on the behaviour of creatures, movements, their lifestyle, and thereby mathematical model is arranged to solve the current issues. To calculate the control parameters, the plant should be modelled using steady-state analysis [14]- [15]. One of the most common and effective approach involves state-space

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averaging to find the system model but is not suited for a higher-order system. Generally, voltage lift circuit-based converter using a large number of parasitic elements which attain higher-order model, so that the system complexity will be more. Hence the work is focused to design the system employing a reduced-order model [16]. In general, a traditional method of ZN- PID controller is implemented in an industrial application cause of its robustness and reliability. In this work system stability is verified through ZN-PID and a range of gain parameters values are found out for the proposed Firefly algorithm. PID controller along with Firefly (FF) Algorithm is discussed here which are more efficient and fast convergence of the optimal solution.

The work contributes to optimizing the performance of converter using Firefly algorithm for speed control and smooth starting of BLDC drive. To reduce the computational complexity of high-order circuits, the proposed converter employed a reduced-order state-space model for modelling. Moreover, the output responses of the converter reaches steady-state quickly, ripple-free, and without evidence of any undershoots or overshoot which makes the system is more suitable for drive application. The combination of optimized high gain Luo converter and BLDC drive possess better performance for the required application under dynamically changing weather conditions. In the existing system, control circuits are needed to sense the voltage and current across the BLDC motor to control the speed, it raises the cost, produces energy loss, and complicates the circuit. To overcome these disadvantages the system completely excluded the additional control circuits and adopting the fundamental frequency of VSI through electronic commutation to diminish the switching losses which improves the system efficiency.

The effort is primarily focused on providing a constant power supply to the BLDC for the hired during periods of low solar irradiation. This can be attained by utilizing an alternative source of energy like a battery through a bi-directional converter [17]. The battery which collects and stored itself by charging through regulated dc supply from the converter and supplying the electric energy by discharging itself to the load under required operating condition. The bi-directional converter [18]- [20] is used to provide charging and discharging control of the battery and power is transferred among two DC sources. Closed-loop regulation of a high gain Luo converter with an optimised control approach is an appropriate and desired combination and BLDC motor provides to enhance the system performance in terms of efficiency, cost-effectiveness, and reliability for the required BLDC drive applications. In case of poor weather conditions, the battery backup storage is rendered for continuous power supply to the motor drive and it yields additional support for the system. The simulation results followed by experimental results, demonstrates the dynamic behaviour of converter, starting and running condition of BLDC under dynamic weather conditions.

The organization of work is as follows: In section 1 elaborates an overview of the design brief, section 2 demonstrates the configuration and operation of high gain Luo converter, section 3 describes the designing and modelling of optimized high gain Luo converter and reduced-order state-space model, section 4 illustrates the proposed work control techniques section 5 describes the investigation and validation of the results, section 6 and 7 discussed the completion of work and references respectively.

II. CONFIGURATION AND OPERATION OF PROPOSED WORK

The system contains solar panel, high gain converter, Voltage source Inverter (VSI) and BLDC motor. In-built encoder is present in BLDC motor for electronic commutation. The designing and specification of solar panel for this application is already discussed in reference [21]. The pulse generator is used to produce the PWM pulse to operate the optimized high gain Luo converter. The unregulated dc output voltage from PV panel is given to high gain converter that converts into regulated output voltage with the support of proposed Firefly algorithm. The classical controllers are failed to providing better results; hence the work is focused to utilize the Firefly algorithm for tuning the control parameters to improve the system performance. The Brushless DC (BLDC) drive receives the controlled and regulated output voltage via a Voltage Source Inverter (VSI), which changes the fundamental switching frequency to efficiently decrease the switching loss. The non-regulated voltage is fed to the Firefly (FF) algorithm to get optimized actual ΔD value and compared with high frequency reference carrier signal to get PWM pulse
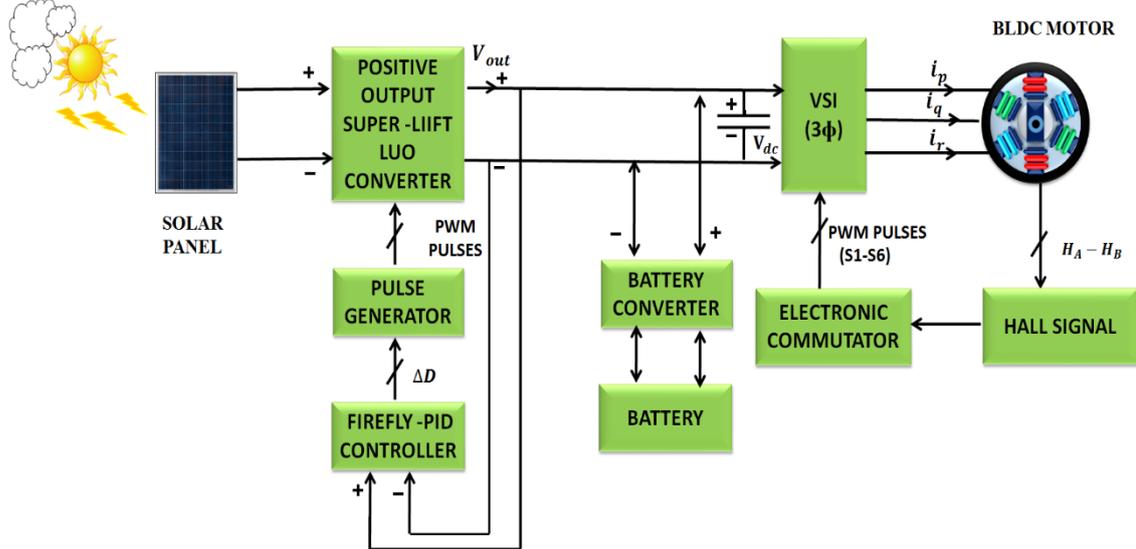
Practically, small amount of power loss appears across the converter due to usage of passive components and it is fed to VSI that converts the regulated DC to AC power supply and given to BLDC motor. In order to eliminate switching loss associated with VSI using fundamental frequency through electronic commutation of drive. Electronic commutation is a process of activating VSI's IGBT switches with pulses based on hall signal generated by hall sensors using in-built encoder. PWM pulses are initiated as the magnetic poles of the rotor get closer to the hall sensors.

The hall signals may low or high to activate switches of VSI. Hence there is no control circuits are needed to senses the current and voltage to manage the speed of motor. In addition, battery is connecting to common dc bus through bi-directional converter. The function of bi-directional converter is dual power flow between battery and dc bus. When absence of solar irradiance battery is allowed to provide required supply to the drive and in case of high irradiance level the excess power stored in the battery itself. In this way system performance is improved under dynamic operating condition.

III. DESIGNING AND STEADY STATE ANALYSIS OF HIGH GAIN DC-DC CONVERTER

It is a topology for sophisticated dc-dc converters [21] using voltage lift technique with single switch S1. The self-lift Luo converter in which the capacitor C achieves voltage lift in the exploration version of the basic Luo converter is illustrated in fig.2. a. It offers several prevalence than the basic converters such as low ripple voltage, low inrush current, high voltage conversion, high power density, simple structure etc. Additionally, one more inductor L2 is included for increased the voltage under peak demand condition.
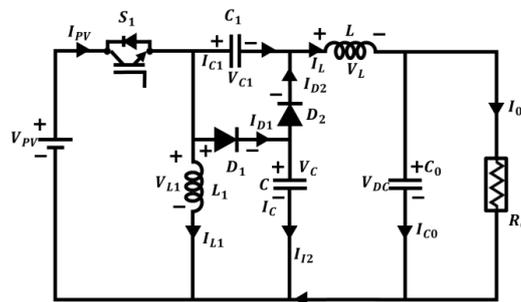

Figure .2. a. Circuit diagram of high gain Luo converter

A. Mode 1: (Continuous Conduction Mode)

The potential drop throughout the inductor in steady state is zero over a period of time. Hence $V_c = V_{pv}$ and $V_{C1} = V_o$. During T- ON the source instantaneous current $I_{pv} = I_{L1} + I_L + I_C$. Inductor L_1 absorbs energy from the source.

In the meantime inductor L absorbs energy from source and capacitor C. Both currents I_{L1} and I_L starts to increase, and C_1 is charged to $V_{pv} = V_{C1}$
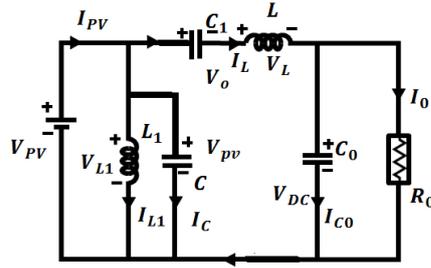

Figure.2. b. Switch on condition of high gain Converter

Where V_{C_1} and V_C are the voltage capacitor C_1 and C respectively. The input voltage is represented as V_{pv}. At the same instant source current will be

$$I_{pv} = I_{L_1} + I_L + I_{C_1} \qquad \text{---------------(3)}$$

I_{pv} is the input current of converter. The inductor current L, L_1 is taken as I_{L_1}, I_L and V_{C_1} is the voltage drop across the capacitor C_1. The permitted ripple current discharge by way of the inductor L, L_1 is defined as

$$\Delta I_{L_1} = \frac{DTV_{pv}}{L_1} \qquad \text{------------------(4)}$$

$$\Delta I_L = \frac{DTV_{pv}}{L} \qquad \text{------------------(5)}$$

Where $\Delta I_{L_1}, \Delta I_{L_2}$ and ΔI_L is the ripple current of inductor L, L_1 and L_2 respectively. Duty cycle ratio of converter is D and total time period is defined as T. The ripple level is considered to be 10% to 30% of the total load current in this case.
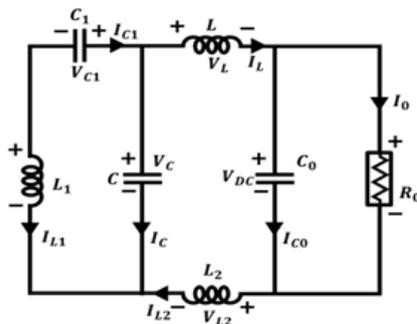

Figure.2. c. Switch off mode of optimized high gain Converter

During T- OFF condition, the source instantaneous current $I_{pv} = 0$. Current I_{L1} flows through capacitor C and diode D to charge capacitor C_1. Inductor L_1 transfers its stored energy to capacitor C. At the same instant, current I_L flows through the $C_0 - R_0$ circuit, the capacitor C and diode D_2 to keep itself continuous. Both currents I_{L1} and I_L starts to decrease. The peak-to-peak variation ratio of capacitor voltage which are used to designing the capacitor value V_{C_1} and V_C

$$\Delta V_{C_1} = \frac{(1-D)T}{C_1} I_{pv} \qquad \text{---------------(6)}$$

$$\Delta V_C = \frac{(1-D)T(I_L+I_{L_1})}{C} \qquad \text{---------------(7)}$$

Where $I_L + I_{L_1} = I_{pv}$, ΔV_{C_1} and ΔV_C are permitted ripple range of capacitor value C and C_1, it is considered to be 1% to 3% of load voltage. In this case T-OFF is the switching-off duration of converter is denoted as (1-D) T, duty cycle

ratio of converter is D and total time period is defined as T. Inductor current is denoted as I_L and I_{L_1}. Input solar current is taken as I_{pv}.

The variation of inductor current is

$$\xi = \frac{D}{V_g^2} \frac{R_o}{2fL_{eq}}$$ ---------------(8)

Where $L_{eq} = \frac{LL_1}{L_1 + L}$

The output voltage variation ratio is

$$\varepsilon = \frac{D}{8V_g f^2 C_o L}$$ --------------(9)

The duty cycle represented is D, R_o is the load resistance and C_o is the dc-link capacitor, V_g is the transfer gain ratio of voltage, switching frequency is denoted as f, L_{eq} is the addition of inductor L and L_1 and it is represented as equivalent value of inductor. The additional capacitor C_1 rather than elementary circuit which helps to lifts the voltage to high value and assumed the value to be larger enough so that

$$V_{in} = V_{pv} = V_C$$ ---------------(10)

The current in inductor I_{L_1} and I_L are high during T-ON condition and low in T-OFF condition. The voltage through inductor L_1 is V_{pv} and $(V_{C_1} - V_{pv})$. Then the equation will be

$$DTV_{pv} = (1 - D)T(V_{C_1} - V_{pv})$$ ------------(11)

By solving the above equation

$$V_{C_1} = \frac{V_{pv}}{1 - D}$$ -----------(12)

Similarly, the voltage across L are $(V_{pv} - V_{C_1} - V_{DC})$ and $-(V_{DC} - V_{pv})$

$$DT(V_{pv} - V_{C_1} - V_{DC}) = (1 - D)T(V_{DC} - V_{pv})$$ ------------(13)

After simplifying (11) and (13), the voltage transfer gain

$$V_g = \frac{V_{DC}}{V_{pv}} = \frac{1}{1 - D}$$ ----------------(14)

Where V_{DC} is the output voltage of dc link capacitor.

B.   Mode 2: (Discontinuous Conduction Mode)

The optimized high gain Luo converter is operated discontinuous mode in the mode 2. During T-OFF condition, duty cycle D is small, the diode current D_2 become zero or switching frequency is small. In this mode the variation ratio of diode current ζ is greater than one

$$\frac{D}{V_g^2} \frac{R_0}{2fL} \geq 1$$ ----------------(15)

Since $\zeta = \frac{D}{V_g^2} \frac{R_0}{2fL}$, Where R_0 is the load resistance, duty cycle ratio of converter D, V_g implied as voltage gain, switching frequency f and L is expressed as the main inductor of converter.

Table 1   Parameter of optimized high gain Luo converter

Sl.No	Parameter	Rating
1	Input voltage (V_{in})	30 V
2	Output Voltage (V_{out})	120V
3	Inductor (L, L_1)	7.141Mh
4	Inductor (L_2)	3.569mH
5	Capacitor(C_1, C_0)	1.2µF,22µF
6	Switching Frequency (f_{sw})	20KHz
7	Input power (P_{in})	746W
8	Output power (P_o)	800W

By using the equation (4), (5), (6) and (7) the design values of inductor and capacitor values are calculated.

C.   Reduced order Model

It is a very effective method [22] for analysing high gain converters and are derived for optimized high gain Luo converter. The reduced order model of converter is explained as follows.

At mode:1

$$\frac{di_L}{dT_{on}} = \frac{V_{pv}}{L_1} \qquad\qquad \text{------------(16)}$$

$$\frac{di_L}{dT_{on}} = \frac{V_{pv}}{L_2} \qquad\qquad \text{--------------(17)}$$

$$\frac{dV_{DC}}{dT_{on}} = \frac{DI_{L_2}}{C_O} - \frac{V_{DC}}{R_O C_0} \qquad\qquad \text{------------(18)}$$

At mode 2:

$$\frac{di_{L_1}}{dT_{off}} = \frac{(1-D)V_{pv}}{L_1} - \frac{(D-1)V_{DC}}{L_1} \qquad\qquad \text{------------(19)}$$

$$\frac{di_{L_2}}{dT_{off}} = \frac{(1-D)V_{pv}}{L_2} - \frac{(D-1)V_{DC}}{L_2} \qquad\qquad \text{----------------(20)}$$

$$\frac{dV_{DC}}{dT_{off}} = \frac{1-D}{C_0} i_L - \frac{1-D}{R_0 C_0} V_{DC} \qquad\qquad \text{--------------(21)}$$

The on-time and off-time periods of switches are represented by T_{on} and T_{off}. The load resistance for the reduced order analysis is considered to be R_0. The state space model is obtained in general as

$$\dot{x}(t) = p_1 x(t) + q_1 V_{pv} \text{ , s=1} \qquad\qquad \text{--------------(22)}$$

$$\dot{x}(t) = p_2 x(t) + q_2 V_{pv} \text{ , s=0} \qquad\qquad \text{--------------(23)}$$

Where $\dot{x}(t)$ is the input variable, p_1, q_1 and p_2, q_2 are the matrices of co-efficient, s=0 says switch-off position and s=1 says switch-on position of converter. By using the above estimated equation (16) to (21), the co-efficient matrices can be defined as

$$p_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{D}{C_0} & \frac{-D}{RC_0} \end{bmatrix} \qquad\qquad \text{-----------------(24)}$$

$$p_2 = \begin{bmatrix} 0 & 0 & \frac{D-1}{L_1} \\ 0 & 0 & \frac{D-1}{L} \\ 0 & \frac{1-D}{C_0} & \frac{D-1}{C_0} \end{bmatrix} \quad \text{-----------------(25)}$$

$$q_1 = \begin{bmatrix} \frac{D}{L_1} \\ \frac{D}{L} \\ 0 \end{bmatrix} \quad \text{----------------(26)}$$

$$q_2 = \begin{bmatrix} \frac{1-D}{L_1} \\ \frac{1-D}{L} \\ 0 \end{bmatrix} \quad \text{----------------(27)}$$

The output equation is defined as

$$y(t) = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} x(t). \quad \text{-------------(28)}$$

The closed transfer function of the system using reduced order model is obtained as

$$G(s) = \frac{2.545e^7}{s^2 + 454.5s + 7.273e^6} \quad \text{----------------(29)}$$

IV. CONTROL ALGORITHM

A. *Charging Control of Battery*

As illustrated in Fig. 1, a bidirectional energy transfer between both the DC bus and storage batteries is performed using power transfer management through bi-directional DC-DC converter. A voltage regulator regulates the DC bus voltage, V_{ref} is the BLDC motor rated DC voltage, which is 120 V. The current regulator controls its battery's charging/discharging current as I_{act}. In current and voltage regulator, a PI controller is utilised to generates duty cycle which is then turned into a PWM signal for the bi-directional converter through common DC-bus.
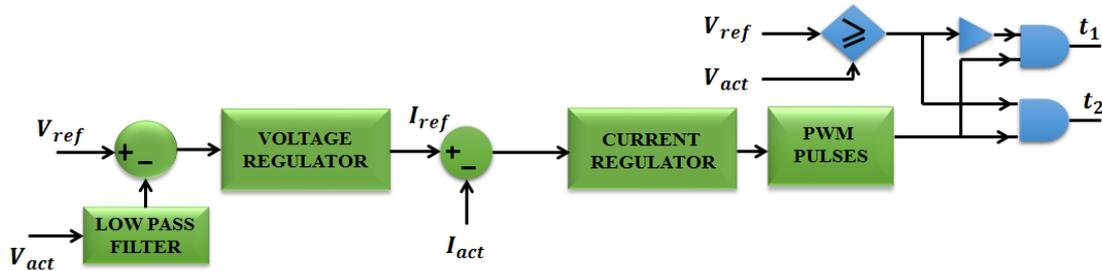
The bidirectional converter operates whether in buck or boost mode at the same time. The voltage of common DC bus controls the operation mode. During night, the solar irradiation is reduced or totally absent causes fall in the voltage of common DC bus. At the time, the controller maintains the reference voltage at its pre-set value by driving the bi-directional converter in charging mode and permitting energy flow from the rechargeable batteries to the DC bus, substantially discharging the battery. In charging mode, only the device t_2 is active, whereas a boost mode operating bi-directional converter circuit is accomplished by a diode in anti-parallel on device t_1. A system voltage rises once the solar energy is available when there is no water pumping is required. Battery charging taking place when the control circuit maintains the reference voltage by driving the bi-directional converter in alternate mode and allowing energy to be transferred from the common DC bus to a rechargeable battery. The gate t_1 is turned on in this instance, and an anti-parallel diode from t_2 is used to construct a circuit of buck converter. If a PV panel provides enough power to drive the pump at maximum capacity, the battery is turned off and there is no storing or draining of the battery. Therefore DC bus voltage is maintained at 120 V, regardless of whether the battery is getting charged/discharge or idle.

B. ZN-PID Control Algorithm

The major goal of the controller design is to reduce the error difference between the actual and reference values. PID controller block in proposed work is to compensate the error signal generated by the comparator. Effective tuning of control signal is an important aspect to design the control parameter. The tuned control signal generates duty cycle related to error signal which is given to high gain converter. The mathematical expression for PID controller in continuous time is defined as

$$r(t) = K_p[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{d}{dt}e(t)] \quad\text{---------------(27)}$$

The error signal is given by

$$e(t) = V_{ref} - V_o \quad\text{---------------(28)}$$

The transfer function of equation (1) is expressed as

$$r(s) = \left[k_p + \frac{K_i}{s} + K_d s\right]e(s) \quad\text{---------------(29)}$$

Where k_p is the proportional gain of converter, T_i is the integral time and T_d is the derivative time. V_{ref} denotes the reference voltage, V_o is the actual voltage from the plant and r(t) is the control output of plant. The simple ZN -PID tuning rules are shown in table II. This the most accurate method for tuned the control parameters effectively. The critical gain $P_{cr} = \frac{2\pi}{\omega}$ where ω is the natural frequency of oscillation of converter [25].

Table. 2 Tuning formulae for ZN-PID controller method

Sl.No	Parameter	Rating
1	Proportionality gain (K_p)	$0.45P_{cr}$
2	Integral Time (T_i)	$\frac{1}{1.2}P_{cr}$
3	Derivative Time (T_d)	$0.125P_{cr}$

C. Firefly-PID Control Algorithm

Use For this dynamic plant ZN-PID controller is suitable to get the initial value which is not for optimal value. Hence, the proposed work approaches to new smart nature inspired heuristic algorithm as Firefly (FF) algorithm. Commonly three basic rules are followed to design the algorithm for the work. (i) Consider all flies are unisex (ii) Attraction and brightness are proportional to each other(iii) The objective function is determined by brightness of flies. The step by step procedure of Firefly algorithm is

Input: control parameters K_p, k_i and K_d ,

Output: Reduce the transient response and steady state error

Step:1 Initialize input values I, γ, β, α, f(x), N

I-Light intensity

γ-absorption co-efficient

α-randomization parameter.

β-attractive co-efficient

r-distance between two flies(values)

f(x)-objective function, where x= (x₁, x₂…. xₙ)ᵀ

N-Population size

Step:2 Assign constant values to get optimum solution for the plant

Select r = 0 for best solution, γ=1, α =0.2, β=0.2, N=25

Step:3 Initialize the position x_i and distance between two flies is calculated using the formula

$$r_{ij} = \|x_i - x_j\| = \sqrt{\Sigma_{n=1}^{d}(x_{i_n} - x_{j_n})^2} \quad\quad\quad \text{----------------(30)}$$

Where r_{ij} -distance between two values in ith and jth position. $x_i x_j$ current location of two nearby values.

Step:4 Calculate error criterion value to minimize the error for tuning parameter.

Step:5 Check condition $I_j < I_i$ .The light intensity of jth position value is lesser than ith position, so flies(values) move towards j to i   and update the new value using the formula.

$$x_i^{p+1} = x_i^p + \beta_0 e^{-\gamma r_{ij}^2}(x_i^p - x_j^p) + \alpha \in_i \quad\quad\quad \text{----------------(31)}$$

$$\beta_0 e^{-\gamma r_{ij}^2}(x_i^p - x_j^p) - \text{Attractive co-efficient}$$

$$\alpha \in_i \text{-random movement of value.}$$

x_i^{p+1} =new location of value, x_i^p -present location of value

Step 6: Calculate and update new intensity value.

Step7: Now ranking the global best solution of control parameters. Repeat 5,6,7 until optimal value converges.

The objective function of Firefly control algorithm for tuning the PID gain parameters is defined as

$$\text{ISE}=\int_0^\infty e^2(t)\, dt \quad\quad\quad \text{---------------(32)}$$

$$\text{ITSE}=\int_0^\infty te^2(t)\, dt \quad\quad\quad \text{----------------(33)}$$

$$\text{IAE} = \int_0^\infty |e(t)|\, dt \qu\quad\quad \text{-----------------(34)}$$

$$\text{ITAE}=\int_0^\infty t|e(t)|\, dt \quad\quad\quad \text{------------------(35)}$$

The equation (32-35) depicted the objective function which is subjected to minimize the error indices.

Table 3 The value of Firefly-PID control parameters based on objective function

Tuned Techniques	Tuned parameters	Error criterion indices			
		ISE	IAE	ITSE	ITAE
ZN-PID	K_p 6 K_i 120 K_d 0.075	0.0048	0.0321	0.0006	0.078
Firefly-PID	K_p 13 K_i =2.2864x10^4 K_d 0.0075	0.0024	0.0314	0.0001	0.0795

The table 3 discussed the error criterion of each control parameter of PID controller, among that ITAE yields better performance. Firefly optimized the Kp, Ki and K_d parameters of continuous time PID Control algorithm hence that the closed loop control system could be executed at the highest efficiency. Moreover, the best solution of gain parameter converges at 14th iteration out of 30th iteration and error value reduced to zero (3.2365e-15). From the table IV, it is observed that ITAE objective function provides the fastest settling time, lowest steady state error and no overshoot or undershoot by means of Firefly based PID gain parameter optimization.

Table 4. Performance evaluation of optimized high gain Luo converter using Firefly algorithm

Sl.No	Tuned techniques	Rise time (secs)	Settling time (secs)	Peak overshoot (%)	Steady state Error(V)	Output ripple (V)
1	ZN-PID	0.52	0.72	0.01	0.02	0.01
2	Firefly-PID	0.09	0.19	0.001	0.01	0.001

V. SPEED CONTROL OF BLDC DRIVE

The speed control of BLDC motor is attained through electronic commutation using VSI. It means that changing the flow current through the stator winding in pre-defined manner using decoder logic. According to the rotor position, the in-built decoder generates hall signals is tabulated in [26]. Six switching pulses are generated for VSI utilizing various configurations from these three hall signals. Every 60[0], hall signals are generated in particular combination of VSI switching for each rotor position. The conduction loss is reduced by operating the VSI in 120[0] conduction mode and also VSI adopting fundamental frequency switching results, high switching loss is eliminated which is rendered by electronic commutation of BLDC motor [27]. The speed value of BLDC drive is based on using fundamental frequency of VSI through which output dc-link capacitor value is estimated. The C_0 value is defined as [23]- [24]

$$C_{0\ high} = I_0/6 \times \omega_{high} \times \Delta V_{DC} \qquad \text{------------(31)}$$

$$C_{0\ low} = I_0/6 \times \omega_{low} \times \Delta V_{DC} \qquad \text{------------(32)}$$

The dc-link capacitors $C_{0\ high}$ and $C_{0\ low}$ correspond to the high and low speed values of a BLDC motor, respectively. ΔV_{DC} is the maximum ripple output voltage and ω_{high} and ω_{low} are the high and low values of fundamental frequency. From the two equation (31) and (32) the highest capacitor value is selected for satisfactory performance even under poor irradiance level.

VI. RESULT VALIDATION AND DISCUSSION

The table 4 illustrates the performance indices ZN-PID controller and FF-PID control algorithm. Initially the system is tuned with traditional controller and then the value is optimized using Firefly (FF) Algorithm thereby system reliability and stiffness of output voltage regulation is well improved. The performance of converter is verified that, it works under continuous conduction mode with minimum switching stress on power semiconductor appliance is illustrated in fig.4.a and performance comparison shown in fig.4.b.The random changes of solar input such as 29V-30V-31V and the converter yields the output voltage of 120V with duty cycle ratio of 0.65 at a 20 KHz operating switching frequency. Whenever the step change of solar input is taken place, response of converter does not sacrifice its performance and it reaches its steady state quickly of about 0.09 secs to its nominal value of 120V which shows the system stability and robustness. The high gain Luo converter is integrated with non-linear nature of solar panel, so that closed loop controller is implemented with the help of optimized control algorithm (Firefly algorithm) for efficient working. The required output voltage should maintain its constant value to meet the load demand under input and load variation. It is clearly notice that the output response of converter is stiff, regulated, efficient and reliable under variable input voltage and load variation.
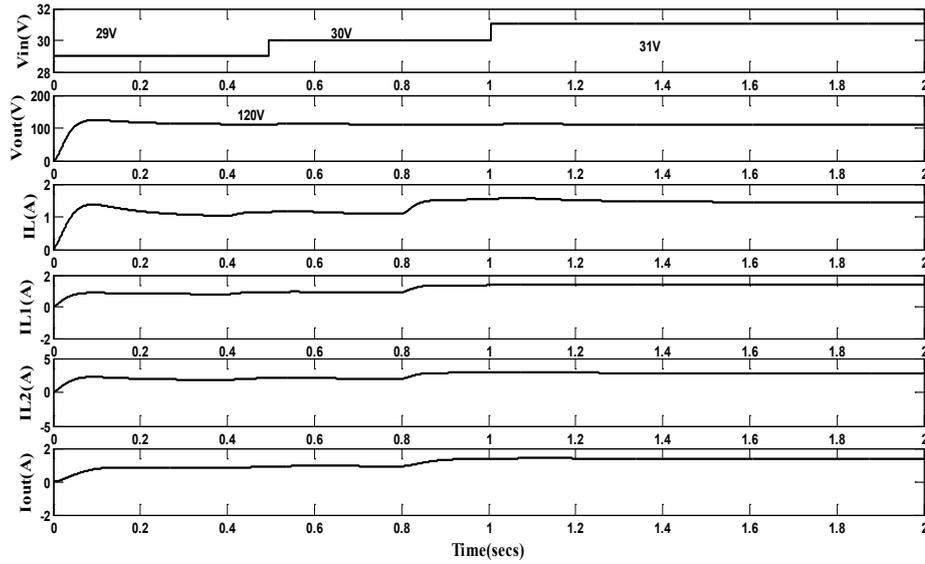
Figure 4.a. Output response of optimized high gain Luo converter of input voltage variation using FF-PID controller method input voltage, output voltage, Inductor current iL, iL$_1$and iL$_2$ and output current.
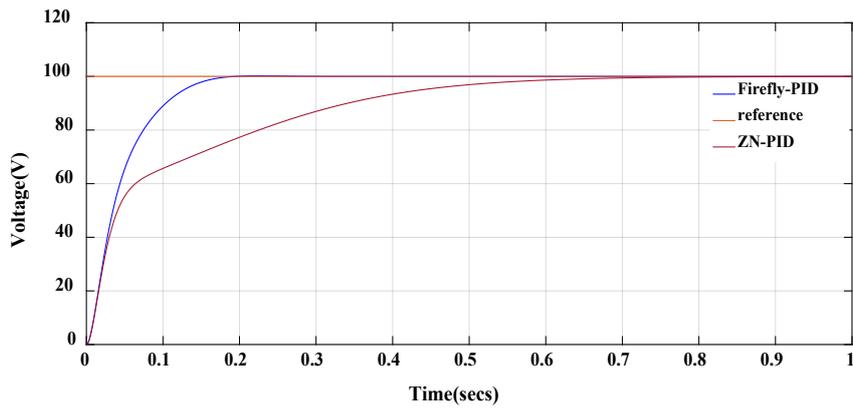

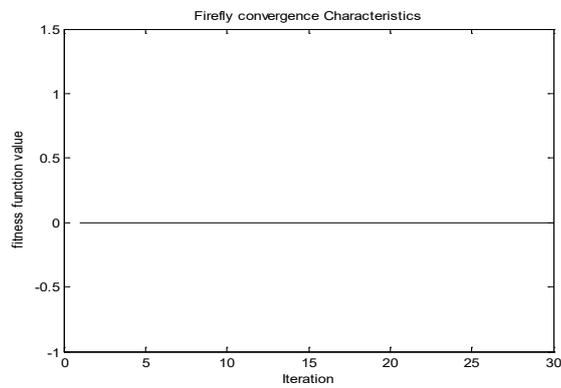**Figure.4. b. Comparison of output response of ZN-PID and Firefly –PID controller**
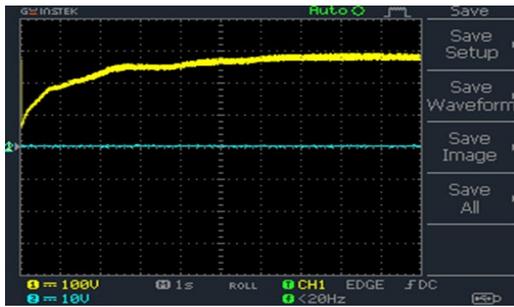

Figure 5. Firefly convergence characteristics

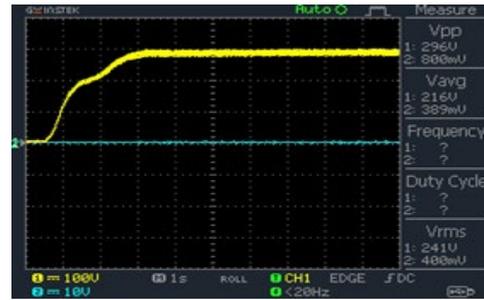**Figure.6. a. Output voltage of optimized Luo converter using ZN-PID controller technique**

Figure.6. b. Output voltage of optimized Luo converter using FF-PID controller technique

The fig.5 illustrates that the firefly convergence graph and it seen that the value of error completely zero.The fig.6.a and fig 6.b.demonstrates the output voltage of proposed high gain Luo converter using ZN-PID and FF-PID controller method.The output voltage reaches it steady state value of 100V with the delay of 0.8 secs is depicts in fig.6.a. The gain parameters of ZN-PID controller are computed manually and are used to tune the values to get optimal solution.In fig.6.b shows the optimized output which attained its steady state value of output voltage without any evident of overshoot or undershoot and it settles at 0.3secs. It is clearly observed that converter can able to track the reference voltage 100V in efficient manner.The non-linear characteristics of solar input is regulated with help of dc-dc converter using optimized algorithm.Here partial shading is not considerd for analysis.The work focuses on improving the performance the converter with control algorithm optimization and leads to provide proper power supply to run the drive under poor solar irradiance condition.
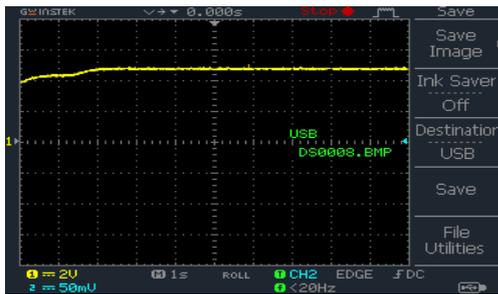

Figure.7.Output current of optimized Luo converter using FF-PID controller technique
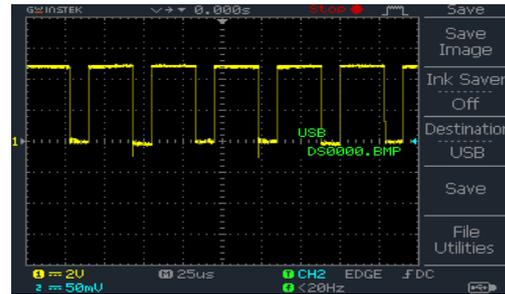

Figure.8.Switching pulses of optimized Luo converter using FF-PID controller technique

The output current of proposed Luo converter using optimized technique is illustrated in fig.7.In contrast with classical converters, current obtained across the voltage lift converter has ripple free and continous output current which ensures smooth starting of BLDC drive through VSI.For optimal operation of converter the duty cycle is adjusted to required output voltage. The duty cycle D=0.65 is taken for the output voltage of 100V and it is exposed in fig.8.
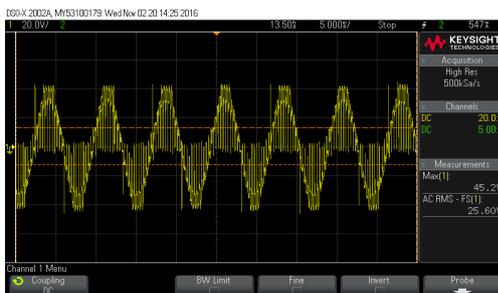

Figure.9.Output voltage of Voltage Source Inverter

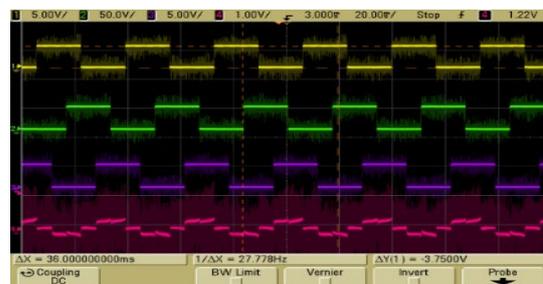**(x-axis 0.1sec/div y-axis 1rpm/div)**

Figure.10.Hall sensor signal and stator current of

BLDC motor

The fig.9.presented the output voltage of VSI in a single channel is shown. The fundamental switching frequency is given by the electronic commutation circuit of BLDC drive. It is obviously clear that, the regulated DC output voltage from the converter is converted into regulated AC voltage using VSI in proper manner without any overshoot or undershoots. The three hall signal are shown in fig.10 that are generated based on rotor position and uniform output current of drive without any ripples is also shown in fig.10. The execution of BLDC motor is not affected under any dynamic climatic condition i.e. input variation or load disturbance.
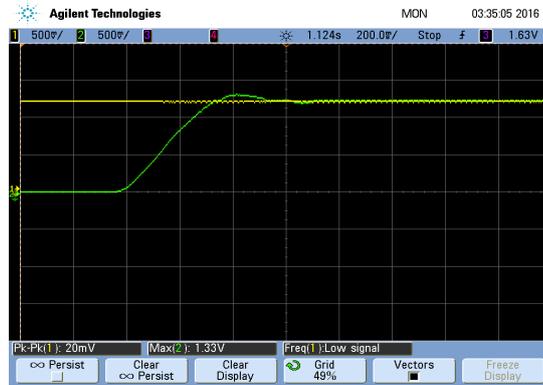

Figure.11.Speed waveform of BLDC motor at 2500 rpm irradiance level of 1000 W/m^2 (x-axis 0.1sec/div y-axis 1000rpm/div)

The speed waveform of BLDC motor under variable irradiance level is delineated in fig.11 a. and fig.11. b. It is evidently observed that, by improving the enactment of converter, the BLDC motor attains smooth starting, reaches it steady output at 0.4secs and minimized the oscillation in effective manner. When maximum irradiance level of 1000W/m² the speed of motor reaches its rated speed of 2500 rpm and under minimum irradiance level of 200W/m² the motor reaches its minimum speed of 1100 rpm.

Table.5 Efficiency evaluation of optimized high gain luo using firefly algorithm

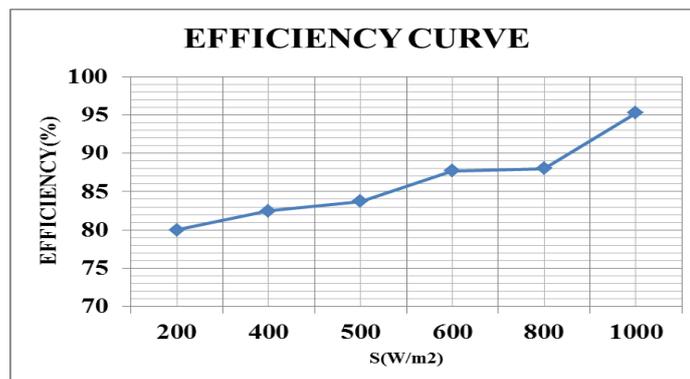| Solar Irradiation (W/m^2)	V_{in}(V)	V_{out} (V)	P_{in} (W)	P_{load} (W)	η(%)
200	24	120	135	108	80
400	29	119.9	235	194	82.5
500	30	120	376	315	83.7
600	31	120.01	474	416	87.7
800	32	119.9	695	612	88
1000	32	120	782	746	95.3

Figure.12.Efficiency curve of optimized high gain Luo converter with different insolation level

Figure 13 Hardware Module

The experimental values are taken for evaluating the efficiency of proposed converter fed BLDC drive. The Table 5 and the fig.12 describes the efficiency of solar fed converter for BLDC drive application using Firefly algorithm under step input change and various load condition. The hardware developed is as shown in fig.13. Moreover, it is noticed that, although the random variation of solar radiation regarding its input voltage variation, output voltage from the optimized converter, and its efficiency is tabulated in Table V. It also stated that, at maximum irradiance of 1000 W/m^2 it reaches the efficiency of 95.3 % and minimum irradiance of 200 W/m^2 it attains the efficiency of 80% .

VII. CONCLUSION

In the proposed work, solar array based optimized high gain Luo converter for BLDC drive application is validated through simulation followed by experimental results. The gain values of PO-SL Luo converter are obtained through ZN-PID controller and that are optimized by employing FF control algorithm. The converter transient response is analysed despite of dynamic weather and variable load condition. Moreover, the system performance is justified under various desired function such as by implementing closed-loop control using FF algorithm for high gain Luo converter, no additional control circuit is utilized to controlling the drive speed and VSI adapts fundamental switching frequency thereby reducing the switching losses resulting reduced circuit complexity and cost effectively. In addition, the voltage-lift technique is employed to increase the low solar panel input voltage to high voltage with no ripple and attain high efficiency using PWM converters by controlling the duty cycle of Firefly algorithm. For an additional support, backup battery storage device assures the continuity and reliability of the power supply to the BLDC drive via bi-directional converter.

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