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PSO-Based LQR Gain Selection for Stand-Alone PV System

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***Abstract*: PSO-based LQR gain selection for the stand-alone PV system. This paper uses DC-to-DC and DC-to-AC converters, including a boost converter and a PWM single-phase full bridge inverter. The purpose of these power converters is to fulfill the desired results acquired from the PV, a source. The voltages generated by the PV are regulated using a boost converter that steps the voltages up to the desired level. These DC voltages are converted to AC voltages by passing them through a DC-to-AC converter to supply the load with power, also known as an inverter. Similarly, the battery, as another source in parallel to the PV system, is used to keep the hold on the charges/ energy. A switching topology deals with all modes of conditions into which this system is driven. The power is supplied to and from the PV to the load, to the battery, and vice versa. Furthermore, an algorithm and a controller are used to overcome the fluctuations caused by the voltages. Particle Swarm Optimization (PSO) and Linear Quadratic Regulator (LQR). PSO helps the LQR set the gain to supply the load with constant and desired voltages by providing the best values. Eventually, an impedance model of this entire project is designed to make comparisons and to get fruitful results.**

Keywords— DC-DC converters, DC-AC converter, PSO, LQR, PV.

I. Introduction

PV, a solar power system, is a source of electrical power. The sunlight is absorbed by the PV panels/ solar panels. Then it is converted to usable electrical power using an internal mechanism within the PV panels. Various aspects can categorize PV systems: grid-connected, stand-alone, building integrated, rack-mounted, residential, utility, rooftop, ground mounted, solar tracking, and fixed-tilt. The PV systems of the current era use the technology of MPPT [1] [2] [3], though it provides maximum power from the sun to the desired load or destination. But MPPT has many disadvantages [4]. Firstly, MPPT is too expensive, making its use uncommon among many users due to the cost factor. It is larger, making it difficult to handle, and MPPT has a shorter lifespan due to numerous electronic components` usage and thermal stress.

Therefore, this paper throws light on an advanced and optimized project that uses a comparatively lower number of electronic components, having not much bigger size as the conventional do have, and the implementation of both PSO [5] and LQR [6] makes it more efficient than the conventional PV systems. The PV [7] system produces electrical power in the same as all do. The voltages acquired from the PV are regulated to the inverter using a DC-DC converter [8], which is a boost converter. The voltages are stepped-up using a boost converter and are then passed through a single-phase full bridge inverter [8]. It changes the DC voltages to AC voltages, which can be used for an AC load. Similarly, a battery is used parallel to the PV to satisfy load requirements uninterruptedly. The entire system works in four different modes. The modes [9] are enlisted below:

i. The PV-generated power and the battery is greater than the load required.
ii. The power generated by the PV is greater than that required by the load, and the battery's power is lesser than that required.
iii. The power generated by the PV is lesser than that required by the load, and the power of the battery is greater than that required.
iv. The PV and battery power are lower than the load's required power.

Similarly, the modes of conduction in this entire power system are controlled by the bi-directional controller. In the first mode, only PV supplies the power to the load and keeps the battery on reserve. In the second mode, the power to the load is supplied by the PV, and at the same time, it supplies power to the battery for its charging. In the third mode, the battery supplies the power to the load. In the last mode, the entire system shuts down as there remains insufficient power to be supplied to the load to avoid any damage.

In the present state of the PV system, one may face fluctuation in the voltages. The voltages are decreased when the load increases and vice versa. Thus, to overcome this very problem, to get the maximum power and a fixed voltage level despite any changes to the system, PSO and LQR are used. They both intelligently work for the efficiency of the system. Plus, an impedance model, too, helps in solving this problem. The impedance model allows one to get the point of maximum voltage level. By achieving that, one can get fixed voltages across the load at any time. Fig. 1 shows the block diagram of the stand-alone PV system with a bi-directional battery.

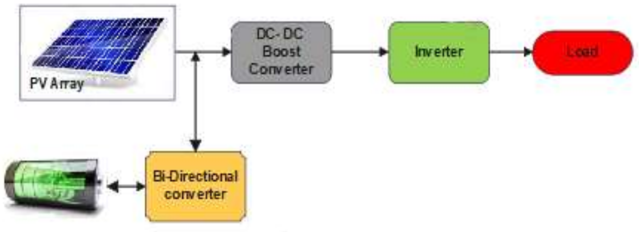

Fig. 1. Stand-alone PV system

II. Ease of Use

A. Module and Efficiency

A 150-watt PV module is very small;l in size. This module might produce 0.75 kilowatt-hours (kWh) daily for an insolation of 5 sun hours/day to satisfy the weather condition. Module output and life are degraded by increased temperature. If possible, flood the ambient air permission and PV modules to reduce this problem. The possible life of the module remains effective for 25 years [10]. The other institute has developed a cell with 44.7% efficiency, making scientists' hopes of reaching the 50% efficiency threshold much more feasible. It is, therefore, good to know more about the such cell, which can produce a large amount of energy to fulfill the load requirement.

B. DC-DC Boost Regulator

In this regulator [8], the output DC voltage is larger than the input DC voltage, and the circuit diagram for the boost regulator is shown in Fig. 2. During the turn-on time of the controlled switch ‘SW’, the input current rises through the inductor. The diode ‘D’ is reverse-biased, and the output capacitor delivers power to the load. During the controlled switch ‘SW’ turn-off time, the input current flows through the inductor ‘L’, diode ‘D’ and capacitor ‘C.’ The inductor current falls until the controlled switch ‘SW’ is turned on in the next switching cycle. The circuit when the switch is open and the collective waveforms are shown in Fig. 3 and Fig. 4.

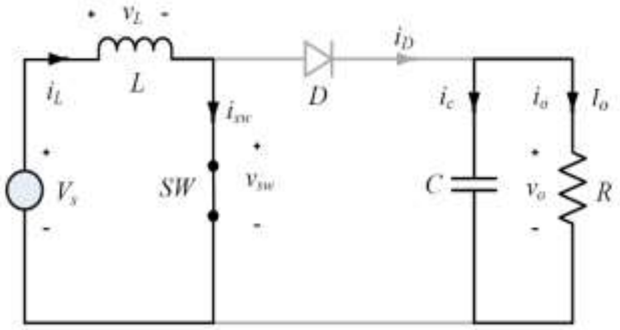

Fig. 2 Boost regulator when switch is close

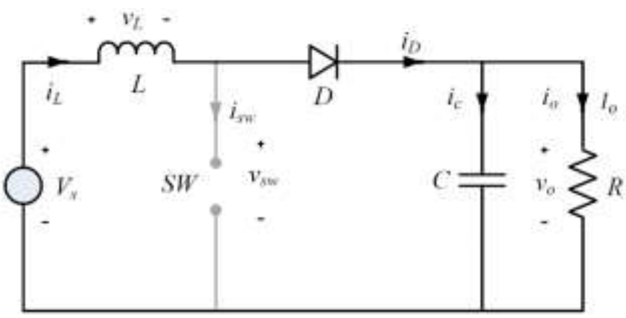

Fig. 3 Boost regulator when switch is open

Similarly, the design of boost regulator acquires the following equations [8].

$$Va = \frac{Vs}{(1-k)} \quad (1)$$

$$Ia = (1-k) * Is \quad (2)$$

$$\Delta I = \frac{k * Vs}{f * L} \quad (3)$$

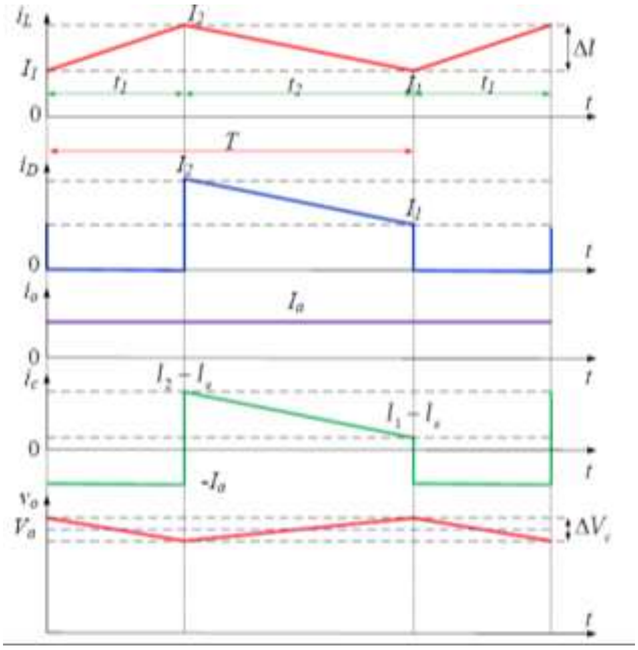

Fig. 4: the collective waveforms

$$\Delta Vc = \frac{k*Ia}{f*C} \quad (4)$$

C. Single Phase Full-Bridge Inverter

The inverter is a power converter that converts the DC voltages to AC voltages with switching devices commonly known as transistors (MOSFETS, IGBTs, etc.) according to desired frequency [11]. The variable output voltage can be obtained by varying the input DC voltage and maintaining the gain of the converters. If the input DC voltage is not controllable, then variable output AC voltage is obtained by varying the gain of the inverter. This is normally accomplished through pulse width modulation (PWM).

The gain of the inverter may be defined as the ratio of AC output voltage to DC input voltage. The output of an ideal inverter is sinusoidal, but practically, it is non-sinusoidal as it contains harmonics. An inverter is called a voltage-fed inverter (VFI) if the input voltage remains constant, and a current-fed inverter (CFI) is when the input current is maintained constant.

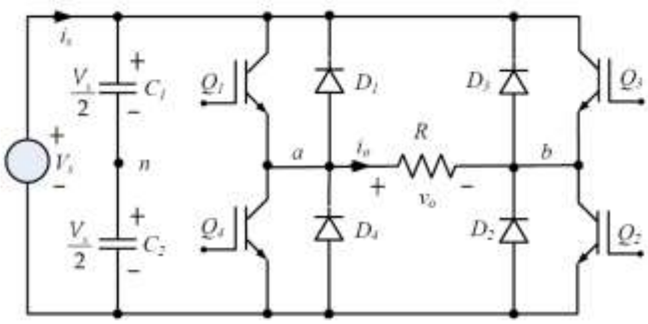

Fig. 5 Single phase full bridge inverter

Q_2, Q_3, and Q_4. This inverter works in a way that the output AC voltages are equal to the DC source voltages in value, $V_o = V_s$. As the switching of the choppers is done in a manner that at first Q_1 and Q_2 remain functional in the first half that is T/2. And in the second half Q_3 and Q_4 as shown in the figure above stay operational to give negative of the source voltages,

V_o = -V_s. The behavior of the voltages and the currents can be witnessed in Fig. 6.

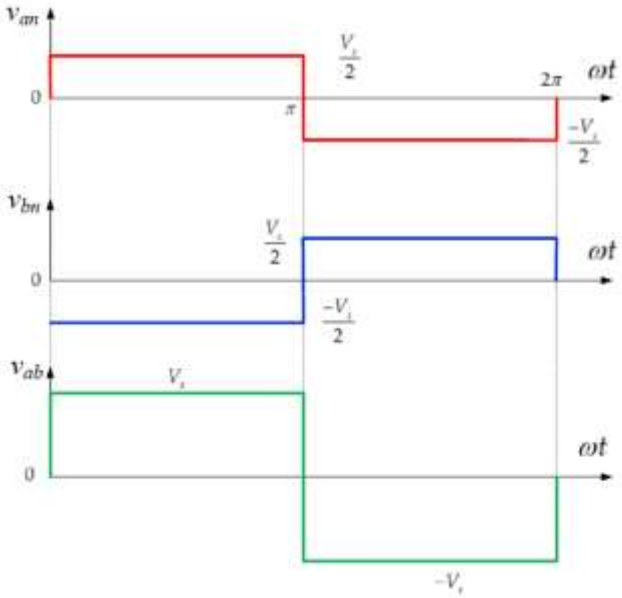

Fig. 6 Waveforms of the output voltages

III. IMPEDANCE MODELLING

Impedance modelling is a technique used to model the proposed PV system in this thesis. This impedance modelling [12] can achieve MPP without any use of MPPT. Plus, this technique is applied to compare the results obtained with this technique and with the use of proposed techniques that are PSO and LQR, though the goal is the same. Similarly, the equations [12] used for the calculations are mentioned below.

$$\frac{Vo}{Vin} = \frac{1}{1-k} \quad (5)$$

$$R_{PV} = \left(\frac{2V_{PV}^2}{V_P^2}\right) R_L \quad (6)$$

$$V_{mpp} = \left(\frac{2R_L}{M^2}\right)\left(I_{mpp} + (1-k)I_b\right) \quad (7)$$

$$V_{PV} = \frac{\sqrt{2}V_{rms}}{M} \quad (8)$$

Furthermore, this technique solves four modes for the proposed thesis. Each of the modes [12] is enlisted below:

i. If the load demands more power than PV can produce at MPP, battery will supply the power.
ii. If the load requires less power than PV can produce, excessive power is used to charge the battery with a bi-directional converter.
iii. Both the PV and battery have more power than the load. The battery is disconnected to avoid overcharging, and the PV supplies load with power.
iv. Neither the PV nor battery has enough power to supply the load, complete shut-down.

In equations 5-8:

$Vo = output\ voltage$
$Vin = input\ voltage$
$k = duty\ cycle$
$R_{PV} = resistance\ of\ PV$
$Vpv = voltage\ of\ PV$
$Vp = peak\ valtage$
$R_L = \ load\ resistance$
$V_{mpp} = voltage\ at\ maximum\ power\ point\ of\ PV$
$I_{mpp} = current\ at\ maximum\ power\ point\ of\ PV$
$I_b = current\ of\ battery$
$M = modulaation\ index$
$V_{rms} = root\ mean\ square\ voltage$

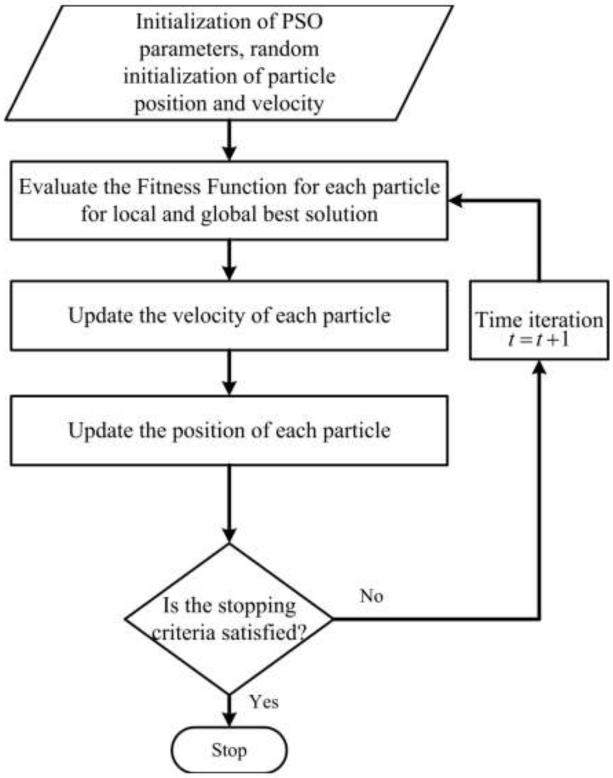

Fig. 7 PSO algorithm flowchart

IV. PARTICLE SWARM OPTIMIZATION ALGORITHM

The design of the electrical system can be the most crucial module. The current era is mainly deply on this system's uninterruptible. It tries to fulfill the demand of electric power supply to commercial, residential and industrial consumers. The power generation, distribution and its utilization demand stable functionality of the power system. The honest and non-stop availability of electricity with minimum problems is the major objective of utility grids and energy providers.

Due to the nonlinear nature of these problems, conventional ways fail to sort them optimally. Therefore, evolutionary algorithms attained a place for such optimization problems [13].

Thus, this research paper introduces PSO to cope with related power systems problems. PSO algorithm is an existing technique inspired by the social behaviour of bird swarms and fish schooling, which was first introduced by Eberhart and Kennedy in 1995 [15]. As a population-based stochastic optimization technique using swarm intellects in the search space, this technique is based on the interaction of a swarm of particles. Each particle has a value for its position and velocity that has to be changed during iterations while considering the particle`s best experience, the best position and the best-achieved experience of all the particles. The updating of the position and velocity of each particle is mandatory for the optimal results to solve the optimization problems. Hence, each particle is based on its movement concerning velocity and position [7]. The algorithm for PSO is written as shown in Fig. 7.

The general equations used to update the velocity and position of a particle are written as [16]:

*particle(i).Velocity = w*particle(i).Velocity ... +(c₁*rand(VarSize).*(particle(i).Best.Position- particle(i).Position)) ... +(c₂*rand(VarSize).*(GlobalBest.Position- particle(i).Position))* (9)

particle(i).Position = particle(i).Position + particle(i).Velocity (10)

where c_1, and c_2 are constants greater than 0 for individual and overall acceleration speed toward the most optimal solution, respectively, 'rand' is a random variable, '*w'* and is an inertia-weighted factor

V. Linear Quadratic Regulator

LQR is a type of optimal control, a well-designed technique that provides feedback gain. LQR structure feedback the given system then multiplies it by gain [K] and subtracts it from the scaled references. The block diagram is shown in Fig. 8.

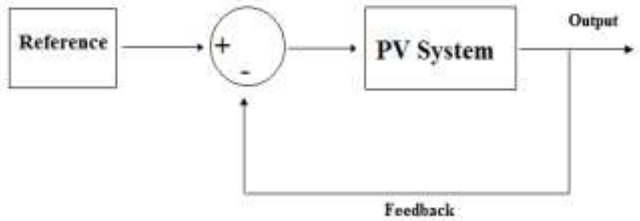

Fig. 8 Block diagram of LQR

With LQR, we find the optimal K by choosing the characteristics important to us, specifically how well the system performs (Q). How much effort (that is, R) it takes to get that performance? The concept of LQR is that we penalize the performance and effort by adjusting Q and R [2]. Designing LQR in MATLAB includes the following steps:

i. Design a model on which we are going to apply LQR.
ii. Adjust Q and R according to a need.
iii. Find the optimal gain using the MATLAB command, "K= lqr(A1, A2, Q, R);" in which A1 and A2 are our inputs and Q and R are the variables.
iv. Simulate the system and adjust Q and R if necessary.

So as long as we understand how Q and R affect the system's behaviour, it is relatively simple to use the "lqr" command in MATLAB to find the optimal gain.

VI. Problem statement

The problems being faced in the PV systems are the voltage fluctuations at the output terminal/ load side, the efficiency of the PV array, system reliability, and optimization of power systems.

Thus, to overcome all the problems mentioned above, this thesis is proposed to get maximum voltages despite voltage fluctuations and to make the existing PV system more efficient and reliable by introducing LQR and PSO. LQR is a controller that shall provide optimal gain/ solution to regulate the voltages at the load terminal, followed by PSO that meta-heuristically solves the voltage-related problems. This thesis shall optimize the PV system by replacing MPPT with PSO.

VII. Proposed system and methodology

The PV system comprises a DC-DC boost converter that is used to step up the DC voltages of the PV module to the load. The DC-DC bi-directional switching topology shifts the power flow to the load from PV to the battery and vice versa. A single-phase full bridge DC-AC converter (inverter) that converts DC voltages to AC voltages. The LQR, and PSO, are used to accomplish the objectives of this thesis by optimization.

Furthermore, the method used to cater to the mentioned problems in the previous section is resolved with a metaheuristic technique using PSO and a controller named LQR to cope with the fluctuations caused due to environmental as well as technical issues.

VIII. Mathematical Modelling and Software Simulation

This section presents the mathematical derivations, software simulations and results. Starting from discussing PV modules and their design according to the desired ratings. After that, designing the DC-DC converter is done, and the circuits are constructed in MATLAB (Simulink). Bidirectional energy storage is designed and attached to the PV system. To get the required output, all the power components are integrated. As mentioned in the previous chapters, an inverter is designed and executed to supply the load with AC power. Consequently, a controller LQR and an algorithm PSO are imposed onto this entire power system to get fruitful results.

Based upon the mathematical modelling, the proposed structure is numerically simulated using MATLAB software. After presenting the complete simulation detail, simulated results are illustrated and discussed comprehensively.

A. Mathematical Calculations

1) PV Module

The design and selection of PV modules is made according to the load's power. The wattage of the load in this thesis is 600W. And the required voltages are 230V-240V. Hence, according to these parameters and keeping the future problems related to the power system in mind. A PV system has a power of 800W selected, 200W of power to overcome any failure in case of any fluctuations caused. Similarly, eight (8) solar panels are used so that two strings of four (4) are connected in a parallel combination, resulting in 70.8V as an output of the PV modules. The catalogue [17] of a single PV panel in a tabular form is shared, in Table I, here, in compliance with which the calculations for the PV modules are carried out.

Each PV panel has a rating of 17.7V and 100W. Thus, a single string of four (04) PV panels would give 70.8V and a power of 400W. Similarly, two strings in parallel combination would give 800W of power and 70.8V of voltage.

The design for an input C filter connected in parallel to the PV module. The purpose of this capacitor is to reduce or suppress voltage ripples. The calculation for its design is performed below.

Calculate the value of a capacitor is given by:

$$C = \frac{I_L}{2fVpp} \quad (11)$$

$I_L = load\ current$

$Vpp = minimum\ ripple\ voltages$

Table I: The catalogue data of PV panel

Electrical and Mechanical Characteristics of PV Panel	Numerical Values
Maximum panel power (P_m)	100 W±%3
Maximum voltage (V_{mp})	17.7 V
Maximum current (I_{mp})	5.65 A
Open-circuit voltage (V_{oc})	22 V
Short-circuit current (I_{sc})	6.21 A
Panel efficiency (%)	15.3
Cell number	36 (4x9)
Panel sizes	1127x676x35 mm
Panel weight	9.5 kg
Operation temperature	40 °C…+85 °C

Thus, Vpp should ideally be always unity, 1. As by Ohm`s law, we know that:

$$V = IR \quad (12)$$

$$I = \left(\frac{240V}{96\Omega}\right)\ for\ 600W\ of\ load \quad (13)$$

$$I = 2.5A \quad (14)$$

$f = 10kHz$

$Vpp = 1V$

$$C = 125\mu F \quad (15)$$

2) Boost Regulator Design For PV

Output power= P_o= 600W

Output voltages= Va= 240V

PV module ratings:

Power of each panel = 100W

The voltage of each panel= 17.7V

As mentioned in the previous section, the PV modules' total power comes out to be 800W and 70.8V according to the combination used.

$$Ia = 2.5A \quad (16)$$

We know that

$$Va = \frac{Vs}{1-k}$$

$$k = 0.705\ or\ 70.5\ \% \quad (17)$$

$$Ia = Is(1-K)$$

$$Is = 8.475A \quad (18)$$

$$L = \frac{0.705 * 70.8}{1 * 10kHZ}$$

$$L = 4.99mH \quad (19)$$

$$\frac{\Delta Vc}{2} < Va$$

$$Va = 240V$$

$$\frac{\Delta Vc}{2} = 0.5$$

$$\Delta Vc = 1V \quad (20)$$

$$C = 176.25uF \quad (21)$$

Therefore, the values for boost converter`s design are:

$$L = 4.99mH$$

$$C = 176.25uF$$

The other parameters` values are also calculated as done below:

$$Isw = Is = 11.299A \quad (22)$$

$$Vsw = Va = 240V \quad (23)$$

$$Ip = Is + \frac{\Delta I}{2} \quad (24)$$

$$Ip = 11.79A$$

$$Iavg(D) = Irms(D) = (1-k) * Il \quad (25)$$

$$Iavg(D) = Irms(D) = 3.33A$$

$$Irms(T) = \sqrt{K} * Il = \sqrt{0.705} * 11.299 \quad (26)$$

$$Irms(T) = 9.487A$$

$$Iavg(T) = k * Il = (0.705 * 11.299) \quad (27)$$

$$Iavg(T) = 7.96A$$

Here the parameters calculated and analyzed are known:

$Isw = switching\ current$

$Vsw = switching\ voltages$

$Ip = peak\ current$

$Iavg(D) = average\ current\ of\ a\ diade$

$Irms(D) = root\ mean\ square\ current\ of\ a\ diode$

$Irms(T) = root\ mean\ square\ current\ of\ a\ transistor$

$Iavg(T) = average\ current\ of\ a\ transistor$

3) Design for Bi-directional Storage

The designing of the bi-directional topology is done as shown below. At first, the ratings of a battery are to be determined. As the PV is generating 800W of power. Thus, the battery that shall be used has the following values:

The current of a battery is

$$I(battery) = \frac{Po}{V(battery)} \quad (28)$$

$$I(battery) = \frac{800W}{70.8V}$$

$$I(battery) = 11.299A$$

Each battery has a 200Ah of capacity. Number of batteries that shall be used to allow this system to back the load up for 17.7 hours are 3 in series (03). Consequently, the total ampere hours rating is 600Ah.

4) Inverter

A single-phase full-bridge inverter [11] is employed for this thesis. As its output voltage equals the input voltage value. That numerically can be expressed as:

$$Vo = Vs \quad (29)$$

$$Vo = 240V$$

$Vo = the\ output\ rms\ voltage$

$Vs = the\ input\ DC\ voltage$

No special calculation is required for the filters in this converter unless a pure sinusoidal inverter is required. For that purpose, the filters' values are calculated. Otherwise, the switches just convert the DC signal into an AC signal at 50Hz, or any, frequency.

5) Impedance Modelling of Stand-Alone PV System

The duty cycle [1] is calculated as using equations from 5-8:

$$k = 0.7914\ or\ 79.14\% \quad (30)$$

The resistance of the PV [12] is:

$$R_{PV} = 8.354\Omega \quad (31)$$

The modulation index M [12] is calculated to be:

$$M = 4.794 \quad (32)$$

The maximum power point voltage [12] of the PV is calculated to be:

$$V_{mpp} = 152.433V \quad (33)$$

The equivalent resistance of the PV and a battery [12] is:

$$Req = 0.64\Omega \quad (34)$$

$$Impp = \frac{Vmpp}{Rpv} = \frac{152.434}{8.3544}$$

$$Impp = 18.25A \quad (35)$$

$$Ib = 33.3A \quad (36)$$

$$Rob = \frac{Vob}{Iob} = \frac{24V}{33.3A} = 0.72\Omega \quad (37)$$

The output voltage of the PV [12] is:

$$Vpv = 70.8V \quad (38)$$

Similarly, the power at maximum power point [12] is:

$$Pmpp = 800.04W \quad (39)$$

Furthermore, as mentioned in the previous section, the modes of conduction, the calculations for each mode are:

a) Mode 1

$$Vpv = 70.8V$$

$$Vbattery = 24V$$

$$k = 0.6610\ or\ 66.10\% \quad (40)$$

The battery current is calculated as:

$$18.24 = 11.3 + (0.339)I_b$$

$$I_b = 20.47A \quad (41)$$

b) Mode 2

The output load power is assumed to be 900W, and the PV power is 800W.

$$R_L = 64\Omega \quad (42)$$

$$k = 0.339 = 33.9\% \quad (43)$$

The battery current I_b is calculated to be:

$$I_b = 24.3109A \quad (44)$$

Lastly, no calculation is required for duty cycle in modes 3 and 4 as only the modulation index is varied merely with a formula discussed in III.

B. Mathematical Modelling

The mathematical modelling [17] of the PV system concerned for this paper uses a state space vector. The modelling for PV module, DC-DC boost converter, and single-phase full bridge inverter.

1) Modelling of PV Module

The photovoltaic cell is a nonlinear device that can be used as a current source in parallel with a diode. Moreover, series and parallel resistors, Rs and Rp, as shown in Fig. 9 and expressed below in equations [17].

$$I = I_{PV} - Io\left[e^{\frac{V+RsI}{Vt.\ a}}\right] - 1 \quad (45)$$

$I = PV\ output\ current$

$V = PV\ output\ voltage$

$$V_t = \frac{Ns * k * T}{q} \quad (46)$$

$V_t = thermal\ voltage\ of\ array\ with\ Ns\ cells\ connected\ in\ series$

$q = charge\ of\ an\ electron = 1.6X10^{-19}C$

$k = Boltzman\ constant = \frac{1.38X10^{-23}J}{K}$

$T = temperature\ in\ k\ of\ PN - junction$

$$I_{PV} = \left(I_{PV,n} + Ki.\Delta T\right)\left(\frac{G}{Gn}\right) \quad (47)$$

$I_{PV,n} = light\ generated\ current\ at\ nominal\ condition$

$Gn = 1000Wm^{-2} = nominal\ irradiance$

$Tn = 25°C = 298K$

$$\Delta T = T - Tn \quad (48)$$

$T = actual\ temperature(K)$

$G = actual\ solar\ irradiance$
$= diode\ saturation\ current\ (Io)$

$$Io = [(I_{SC,n} + k_i\Delta T)/(e^{\frac{V_{oc,n}+k_v\Delta T}{a*Vt}} - 1)] \quad (49)$$

$kv = open - circuit\ voltage\ or\ temperature\ co - efficient$

$ki = short - circuit\ current\ or\ temperature\ co - efficient$

$Isc = short - circuit\ current$

$Voc,n = open - circuit\ voltage$

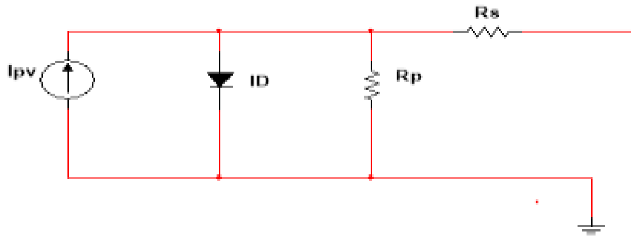

Fig. 9 PV cell internal structure

In both ON and OFF modes of operations [17], let x be a state space vector for the operating mode.

$$x = \begin{pmatrix} Iin \\ V_o \end{pmatrix} \quad (50)$$

Switch OFF

$$\dot{x} = A1.x + B1.Vin \quad (51)$$

Switch ON

$$\dot{x} = A2.x + B2.Vin \quad (52)$$

The average state space mode is:

$$x = Ax \dot{+} B.Vin \quad (53)$$

When switch is OFF, by KCL we get:

$$\frac{d(Vo)}{dt} = -\frac{Vo}{RC} \quad (54)$$

The state-space mode is:

$$\dot{x} = \begin{pmatrix} Iin \\ Vo \end{pmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \left(-\frac{1}{RC}\right) \end{bmatrix} . \begin{pmatrix} Iin \\ Vo \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix} .Vin \quad (55)$$

When switch is ON, by KCL we get:

$$\dot{x} = \begin{pmatrix} Iin \\ Vo \end{pmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ -\frac{1}{C} & \left(-\frac{1}{RC}\right) \end{bmatrix} . \begin{pmatrix} Iin \\ Vo \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix} .Vin \quad (56)$$

Thus, the mathematical model in state space of the boost converter is determined by averaging technique as:

$$\dot{x} = \begin{bmatrix} 0 & -\frac{1-k}{L} \\ \frac{1-k}{C} & -\left(\frac{1}{RC}\right) \end{bmatrix} . \begin{bmatrix} Iin \\ Vo \end{bmatrix} . \begin{bmatrix} \begin{pmatrix} \frac{1}{L} \end{pmatrix} \\ 0 \end{bmatrix} .Vin \quad (57)$$

3) Modelling of Linear Quadratic Regulator as Feedback Controller

LQR is used to control the regulation of the voltages to the load. A state-space technique is used for its design. The state-space calculations [18] are as follow:

$$x = Ax + Bu \quad (58)$$

$$y = Cx + Du \quad (59)$$

A is a system, B is the input matrix, and C is the output matrix. Thus, to establish linear feedback around the system above, a linear feedback law can be implemented and is visible in Fig. 10.

$$u(t) = -Kx(t) + r(t) \quad (60)$$

$K = feedback\ matrix\ of\ order\ m * n$
$r(t) = reference\ input\ vector$
A closed loop system is derived as:

$$x(t) = (A - BK)x(t) + Br(t) \quad (61)$$

The system is stable only if the system matrix (A-BK) has all its eigenvalues in the left half plane. Hence, selecting the K matrix, which makes the system stable, is the most important part of the controller`s design.

$$L = 5mH$$
$$k = 0.7\ or\ 70\%$$
$$A = \begin{bmatrix} 0 & -60 \\ 1702.13 & -59.102 \end{bmatrix} \quad (62)$$

$$B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} = \begin{bmatrix} 200 \\ 0 \end{bmatrix} \quad (63)$$

$$C = [1 \quad 0] \quad (64)$$

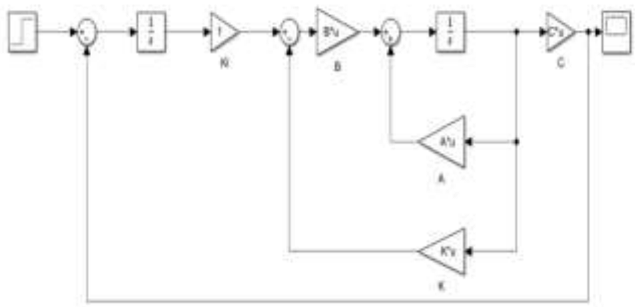

Fig. 10 State feedback controller with reference tracker

4) Modelling of Single-Phase Full Bridge Inverter

A single-phase-full bridge inverter works in two modes of operation. In case of resistive load, the free-wheeling diodes shall be in the reverse-biased state. As discussed in the previous section, the switches convert a DC signal to an AC signal. Thus, in the first mode, Q_1 and Q_2 operate as discussed in the previous section and in the second mode Q_3 and Q_4 function. The calculations according to that are [17]:

$$Vo = Vs \quad (65)$$

$$Io = \frac{Vo}{R} = \frac{Vs}{R} \quad (66)$$

$Vo = output\ voltage$

$Vs = source\ or\ input\ voltage$

$Io = output\ current$

$R = load - resistive$

Thus, by state-space technique, let k be a duty cycle for the mode in which Q1 and Q2 work. And (1-k) for the second mode of operation. The state variables are numerically expressed as:

$$x_1(t).\ x_2(t) = [Io \quad Vo]$$

$$[\dot{X}1 \quad \dot{X}2] = [\dot{Io} \quad \dot{Vc}]$$

$$\dot{X}1 = -\left(\frac{k}{L}\right).x_2 + \left(\frac{k}{L}\right).u \quad (67)$$

$$\dot{X}2 = -\frac{k}{C}.x_1 + \frac{1}{RC}.x_2 \quad (68)$$

Eventually, the above expressions are useful for a PWM single-phase full bridge inverter and to make it valid for a pure sinusoidal AC signal above $\dot{X}1$ and $\dot{X}2$ are multiplied by the following expression.

$$V = Vm.\sin(wt) \quad (69)$$

$w = 2\pi f$

$f = frequency$

$t = time\ period$

$Vm = peak\ or\ mean\ voltage$

C. Simulation Results

IX. CONCLUSION

Eventually, this section covers the conclusion of the paper. Similarly, in this current paper, a two-stage PV system is worked on with power storage as a backup. The PV system is unstable in an open loop with no controller. The power fluctuates, and it does so concerning the ratings of the load. The power decreases as the load is reduced and vice versa. Thus, PV system in an open loop comes out to be only stable with a fixed output load that is resistive for this particular thesis.

On the other hand, the same PV system is driven in a close loop with two different controllers: a PID controller and an LQR controller, as shown in Fig. 11 and Fig. 12. Each gives different responses, and in the end, the optimal gains are optimized using PSO algorithm iteratively. In the same manner, the PID controller works quite well, giving required results efficiently and smoothly, having a rise time of 14.356ms, overshoot of 0.505%, and settling time of 17.726ms, as shown in Fig. 13. Whereas, when the same system is run using an LQR controller there exists overshoot, rise time, and settling time. Plus, taking much more time than PID to output the required results.

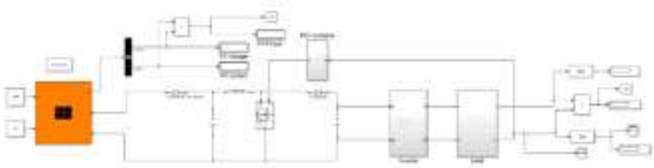

Fig. 11 Block diagram of PV system with PID controller

Consequently, as aforementioned, the major work committed to being done is of PSO-based LQR gains selected. Therefore, the PSO algorithm is used to get the optimal gains against iterations that are eight (08) in number with a rise time of 2.173s. The algorithm optimizes the optimal gains [K_1 K_2]= [4.4846 0.5941] used in an LQR to complete this research paper, as shown in Fig. 14 and Fig. 15.

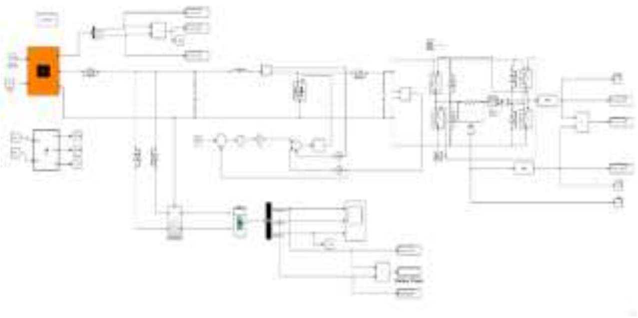

Fig. 12 Block diagram of PV with PSO-based LQR controller

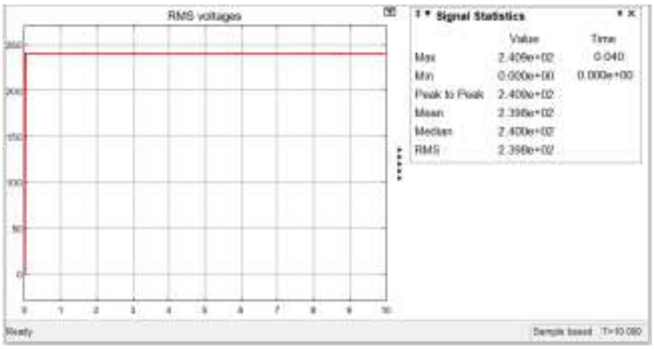

Fig. 13 RMS voltages using PID controller

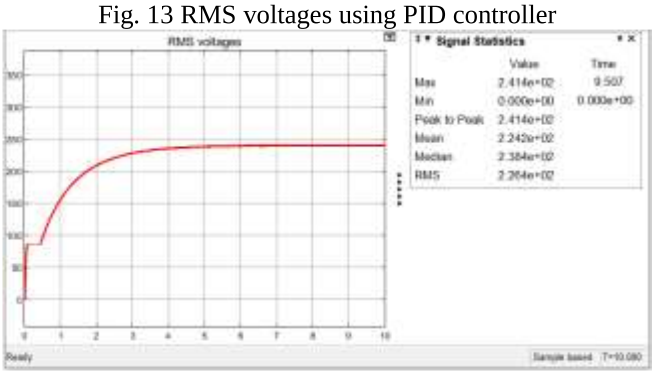

Fig. 14 RMS voltages using PSO-based gains

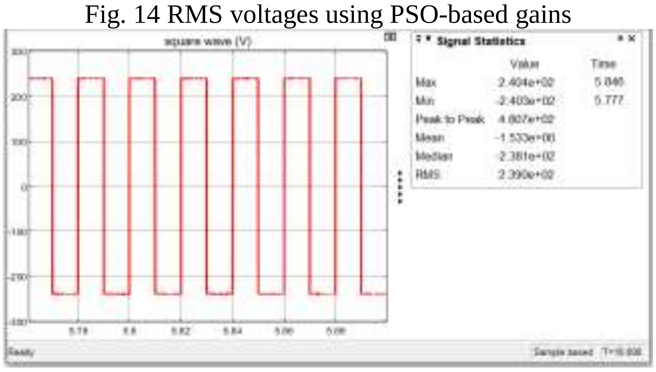

Fig. 15 Square-wave voltages using PSO-based gains

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The authors declare they have no conflicts of interest to report regarding the present study.

CONFLICT OF INTEREST

The Authors declare that they have no conflicts of interest to report regarding the present study.

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