An Enemy to Friend Optimization Based Dc To Dc Converter for Building Integrated Photovoltaic (BIPV) System

N.KamalaKannan[1], Dr.S.M.Ramesh[2]

[1]Research Scholar, Faculty of Electrical Engineering, Anna University, Chennai - 600025, Tamil Nadu, India.
[2]Professor, Department of Electronics and Communication Engineering, E.G.S.Pillay Engineering College, Nagapattinam - 611002, Tamil Nadu, India.
Corresponding Author mail id: kamalakannandr55@gmail.com

Abstract: *The Photovoltaic (PV) systems are mainly implemented to convert the solar irradiance into electrical energy. The PV modules used in Building Integrated PV (BIPV) is installed at separate orientations and angles. In the traditional systems, the performance of the PV modules are easily affected due to the mismatch of electrical parameters. Also, its power configurations are highly difficult, which leads to reduced reliability and energy efficiency. Thus, this paper intends to introduce a new DC-DC converter by implementing a novel Enemy to Friend (E2F) algorithm. Initially, the solar irradiance obtained by the solar panel is converted into DC by using the Maximum Power Point Tracking (MPPT). In which, the Pulse Width Modulation (PWM) is generated based on the optimization process, for this purpose, an E2F algorithm is implemented. In this technique, the enemy who has the minimum anger (i.e. the duty cycle which has the minimum value) is selected, then make it as a friend. The output power obtained after implementing the DC-DC converter is given as the input for inverter. Here, the Indirect Sliding Mode Control (ISMC) is utilized for controlling the power system. Finally, the output of inverter is either connected to grid or load. In simulation, the efficiency of the proposed optimization based controlling strategy is evaluated and analyzed by using the measure of DC-DC converter output and inverter output at varying temperature.*

Keywords: *Building Integrated Photovoltaic systems, Maximum Power Point Tracking, Pulse Width Modulation, Enemy to Friend Optimization, DC-DC Converter, and Indirect Sliding Mode Control* **.**

1. Introduction:

PHOTOVOLTAIC (PV) system are connected with a series of PV modules, in which each module have a string of PV cells [1, 2]. This system generates the electrical energy from the solar irradiation incident with the use of PV modules. In most of the renewable energy applications, the solar cells, wind turbines, fuel cells, and batteries are required due to its maximum utilization. In PV system, the source output current and voltage are must be non-zero for saving the energy during maximum renewable energy extraction. The reason of using PV is to transform the solar irradiance into the electrical energy. Normally, the PV system and battery are connected to a unidirectional and bidirectional part of the converter. The Building Integrated Photovoltaic (BIPV) [3, 4] is the widely used system that integrates the large area PV panels into the building envelope. The major reasons of using BIPV are, it reduced the cost, and increased the lifecycle of PV. A typical BIPV system contains the PV modules, charge controller, and power storage system [5].

When the solar radiation is available, the Maximum Power Point Tracking (MPPT) [6, 7] is implemented to generate the maximum power. Moreover, the MPPT automatically

determines the output current or output voltage of the PV system under a given temperature and irradiance [8, 9]. It efficiently power increase from the PV module to load, and improves the operating lifetime of the PV system. Different types of MPPT methods are developed based on the features of convergence speed, hardware requirements, range of effectiveness, cost, and sensors. This type of converter matches the features of the solar panel with the load. Also, the PV system is connected to a microgrid with the use of DC-DC converters [10]. Moreover, a control signal is applied to the converters in order to regulate the terminal voltage of PV system. It attains the maximum efficiency during power delivery to the load.

A. Problem Identification

Typically, the photovoltaic materials replace the conventional materials that are used for building the power system [11, 12]. The maximum amount of power is extracted from the solar irradiance with the use of MPPT. In the traditional works, the Perturb and Observe (P&O) [13, 14] is one of the widely used simplest technique, but it has some major problems:

- Due to the rapid change of irradiance, this technique was less efficient, and not highly intelligent.
- Due to the new duty cycle value or irradiance, it is incapable to verify the new output power value.
- Continuous oscillations at low irradiance.
- Slow response time.

Due to these problems, the proposed work aims to develop a new optimization based DC-DC converter.

B. Objectives

The main contributions of this work are as follows:

- To efficiently perform DC to DC conversion, a Maximum Power Point Tracking (MPPT) is implemented.
- To generate the Pulse Width Modulation (PWM), a novel optimization algorithm, namely, Enemy to Friend (E2F) is proposed.
- To invert the output DC current, an Indirect Sliding Mode Control (ISMC) is implemented.

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C. Organization

The remaining sections that present in the paper are structured as follows: Section II reviews the existing controlling strategies for a BIPV system. Then, in Section III, the clear description about the proposed E2F optimization based controlling technique is presented. In Section IV, the simulation results of existing and proposed systems are analyzed. Finally, the paper is concluded and the enhancement that can be implemented in future are stated in Section V.

2. Related Works:

Li, et al [15] suggested a Maximum Power Point Tracking (MPPT) control strategy to analyze the effect of DC/DC converter on the Photovoltaic (PV) system. Here, the feasibility and availability of the control strategy was verified in order to evaluate the performance of PV system. Also, the relationship between the Variable Weather Parameters (VWP) and control signal are estimated with the use of curve fitting technique. In which, the curve fitting errors were detected and rectified with the use of correction term. *Ling, et al* [16] designed a Second Order Sliding Mode (SOSM) controller for synchronizing the buck DC-DC converter. In this design, the steady state switching frequency was controlled by implementing a hysteresis method. The main intention of this model was to attain fast transient response, stability, and robust operation. The limitation that observed from this paper was, it required to improve the efficiency of controlling. *Das and Agarwal* [17] implemented an energy recovery scheme for analyzing the efficiency of DC to DC converter. This controller contains the components of coupled inductor, intermediate capacitor, and passive clamp network. The voltage gain was increased by using the intermediate energy storage capacitors. From the paper, the main drawbacks of using DC-DC converters were analyzed, which includes:

- An increased peak current on the input side affected the magnetic components.
- Increased conduction loss due to the increased duty cycle.
- Diode reverse recovery.

Choi and Jung [18] developed an enhanced Power Line Communication (PLC) strategy for increasing the reliability of the DC micro-grids. The motive of this paper was to improve the performance of communication by solving the power conversion problem. In this work, the SFM-DBCS strategy was employed to avoid the communication confliction by controlling the DC bus voltage. The benefits of this paper were, it overwhelmed the problems of additional circuit, inaccuracy of control signal and reduced communication reliability. *Cha, et al* [19] presented an efficient DC-DC converter for reducing the conduction loss and increasing the efficiency of PV micro-inverter. The suggested converter incorporated the full-bridge type voltage doubler and active resonant clamp circuit. The advantages of this converter design were increased efficacy and density.

Banerjee, et al [20] implemented a sliding mode hysteretic control strategy for providing a robust dynamic response with reduced cost. Here, the Pulse Width Modulated and Proportional Integral (PWP-PI) controller was used for maintaining a constant current reference surface. The major benefit of this control strategy was, it could be used in other surfaces and converter topologies. However, this paper required to minimize cost and to increase the efficiency. *Sajadian, et al* [21] recommended a Z-source inverter based MPPT for a PV system. In this paper, the Model Predictive Control (MPC) was used to evaluate the predicted value of the system states by determining an optimal switching schedule. The steps that involved in this design were as follows:

- The cost function was reduced by predicting the behavior of the system based on the switching configurations.
- The possible switching configurations of the converter were identified.

Kim, et al [22] implemented an isolated double step down converter for increased the efficiency of the distributed power system. In this paper, the transformer saturation problem was solved by connecting the DC blocking capacitor with the transformer. Also, the switching loss was avoided with the use of double step down function. The major benefit of this paper was, it was highly suitable for various applications with increased step-down voltages. *Kolsi, et al* [23] analyzed the design of DC to DC converter for optimizing the energy of PV system. This mechanism followed two principles, which includes:

- During the steady state operations, the value of inductance was greater than the inductance of boundary.
- The filter capacitance was larger than the boundary capacitance for limiting the output voltage of the converter.

The main motive of this paper was to improve the efficacy of the converter. However, it has the limitation of increased loss in the PV system. *Zhao, et al* [24] provided an overview about the Dual Active Bridge (DAB) – Isolated Bidirectional DC-DC Converter (IBDC) for analyzing the efficiency, cost, and reliability of the link power conversion system. Here, five different types of switches were used for determining the topology of IBDC. *Subudhi and Pradhan* [2] surveyed some MPPT techniques to analyze the suitable one for PV systems. In this work, the detailed description about the features and number of control variables that involved in this design were discussed. *Wen, et al* [25] introduced a Dual Active Bridge (DAB) DC to DC converters for increasing the efficiency of distributed power systems. Here, an advanced optimization methodology was suggested in order to reduce the power loss. The major considerations of this work were as follows:

- During an optimization, the losses such as transformer loss, power loss components, conducting loss, and switching loss were considered.

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- Also, the non-active power and Zero Voltage Soft-switching (AVS) were considered in the suggested optimization technique.

Dargicevic, et al [26] investigated the DC Microgrid (DC-MG)architectures, and applications of various smart grid systems. The motive of this paper was to reduce the stray current and propagation of disturbances. Also, the topologies of DC-MG were stated in this paper, which includes single bust topology, reconfigurable topology, and multi-bus topology. The functionalities of DC-MG that observed from this study were as follows:

- Power quality
- Stability
- Coordinated control
- Grid support capability
- Flexibility
- Scalability and redundancy

Fletcher, et al [27] developed a high speed current differential approach for detecting the faults in a power distribution system. Here, the synchronization error was reduced by analyzing the current behavior of the power system at varying load conditions. *Hsieh, et al* [28] improved the effectiveness and voltage gain of the distributed power system by introducing a high step-up DC to DC converter. In this design, two diodes and two capacitors were added to reduce the power loss and voltage spike on the switch. Also, the Continuous Conduction Mode (CCM) and the Discontinuous Conduction Mode (DCMM) were used to analyze the operations of the converter. *Elsayed, et al* [29] discussed and analyzed the feasibility of DC distribution systems and the microgrids. The elements that considered in this survey were, DC loads, renewable energy sources, data centers, and storage. From this work, it was analyzed that the stability of the power system was preserved by eliminating the oscillations and maintaining the impedance value. *Engel, et al* [30] implemented a Dual Active Bridge (DAB) DC-DC converter for compensating the phase currents of unbalanced transformers. The motive of this paper was to increase the accuracy of the simulation by reducing the oscillations in the output current. Moreover, a unique method was used to attain a symmetrical short circuit impedance in a medium voltage transformer. The advantage that observed from this work was, it efficiently balanced the three phase currents by employing a controlling strategy.

From the survey, it was analyzed that the existing control strategies have both advantages and disadvantages, but it mainly lacks with the following limitations:

- Increased power loss
- Poor tracking
- Less efficient due to the change of irradiance
- Required to improve the performance of controlling strategy
- Increased duty cycle and conduction loss

In order to solve these issues, this work aims to introduce an optimization based controlling strategy for a BIPV system.

3. Proposed method:

In this sector, the detailed description about the proposed converter design is presented. The motive of this paper is to develop a new optimization based DC-DC converter for a BIPV system. Also, this work aims to observe the changes that appeared in the solar irradiance and temperature. Then, it computes the duty cycle by using an Enemy to Friend (E2F) technique with the use of MPPT. Here, the novelty is implemented in the DC-DC converter by using an E2F optimization algorithm. The flow of the proposed system is shown in Fig 1, which contains the stages:

- Solar Irradiations
- DC-DC Converter
- Inverter
- Performance analysis

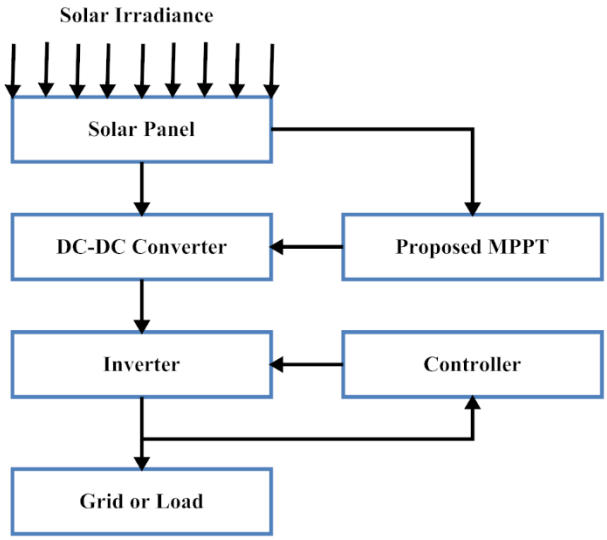


Fig 1. Flow of the E2F based DC to DC converter design

The overall simulation illustration of the proposed system is depicted in Fig 2, which contains the components of PV module, E2F optimization based MPPT technique, DC-DC converter, three phase inverter, SMC, non-linear load, and grid.

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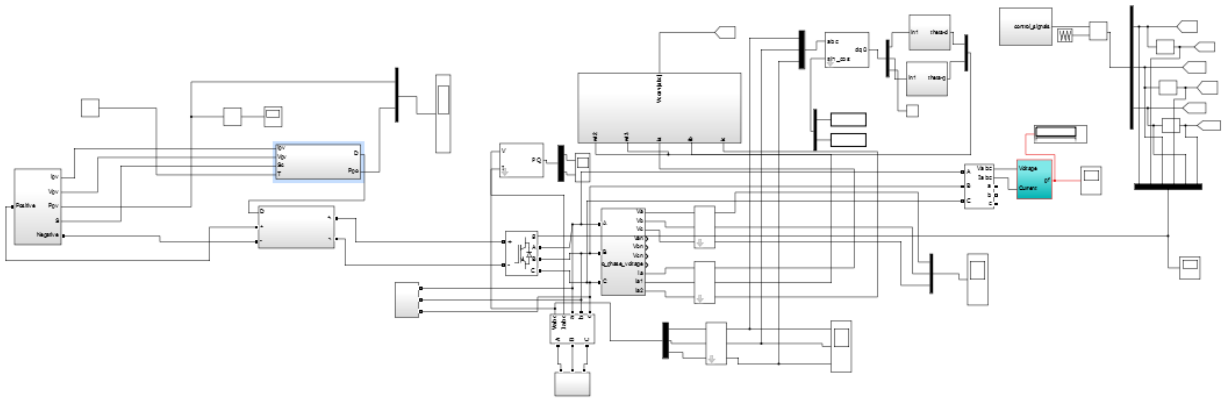


Fig 2. Simulation diagram of the overall system

D. Solar Irradiance

In the large scale embedded PV systems, solar irradiance and its impact are the major issues. It is characterized based on the short time fluctuations, which leads to intermediate power shortage, insufficient storage, and fluctuations in microgrid. Typically, the solar irradiance is difficult to determine due to the severity in grid voltage and power fluctuations. In this work, the solar irradiance is converted into an electrical energy by performing a DC-DC conversion with the use of MPPT. During this conversion, the light is converted into electricity based on a photovoltaic process, then the electrothermal process is performed for converting the energy into heat. Moreover, the solar energy conversion is highly depends on the solar cell and photovoltaic module. Here, the solar cell is specified as follows:

$$I = I_{ph} - I_s * \left(e^{\left(\frac{V+I*R_S}{N*V_t}\right)} - 1\right) - I_{s2} * \left(e^{\left(\frac{V+I*R_S}{N_2*V_t}\right)} - 1\right) - \frac{(V+I*R_S)}{R_p} \quad (1)$$

$$I_{ph} = I_r * \left(\frac{I_{ph0}}{I_{r0}}\right) \quad (2)$$

Where, I_s, I_{s2} represents the diode saturation currents, I_{ph} indicates the solar generated current, V_t denotes the thermal voltage, I_{ph0} represents the solar generated current for irradiance I_{r0}, R_p denotes the parallel resistor, R_s denotes the series resistor, I_{sc} defines the short circuit current which is I_{sc}=7.34 A, N_2, N indicates the quality of factors which are $N_2 = N = 1.5$, and $V_{oc} = 0.6V$.

E. DC-DC Converter

After obtaining the power from solar panel, the DC-DC converter is used to convert the power, for this purpose, the Enemy to Friend (E2F) algorithm is implemented. Typically, the DC-DC converters has the capability to operate at increased switching frequency. The simulation illustration of the proposed DC to DC converter is shown in Fig 3. Also, it acts as an interface between the load and PV panel, which efficiently avoids the power loss. It gets the input as an average output voltage, and attains an optimum power of the PV system. Furthermore, this converter is used to maintain the voltage, current, and power at varying duty cycle, temperature and irradiance. In which, the MPPT is used for optimizing the match between the utility grid and solar array. The main reason of using MPPT in DC-DC converter is, it efficiently increased the power of solar cells. Moreover, it reduces the installation cost and improves the efficiency of energy conversion. In this work, the MPPT is mainly used to efficiently extract the power from the solar panel based on the duty cycle of the PWM.

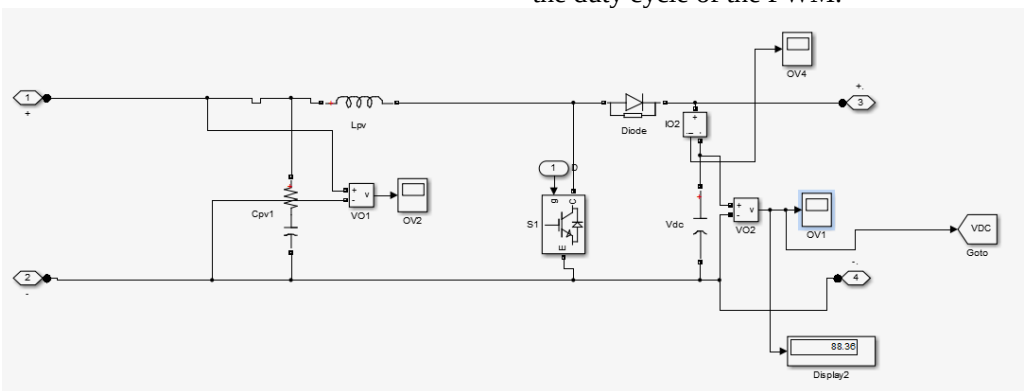


Fig 3. Simulation diagram of DC-DC converter

The E2F algorithm is developed based on the couplet of,

- *Without Ally, Who Fights with Twofold Enemy O'ermatched, Must Render One of These a Friend Attached*

At first, the number of enemies are initialized, and their anger are estimated by computing the duty cycle based on the voltage and current. Then, the duty cycle of each enemy is collected and the enemy who has the best duty cycle is selected. After that, the enemy who have the minimum anger is selected and made as a friend. Consequently, the PWM is generated based on that duty cycle, based on this process, the DC to DC conversion is performed.

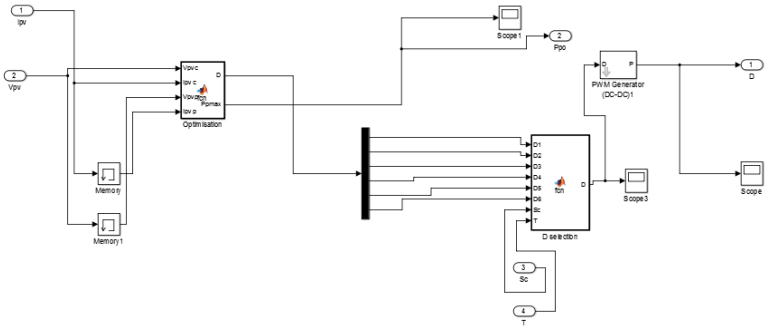


Fig 5. Simulation diagram of E2F algorithm

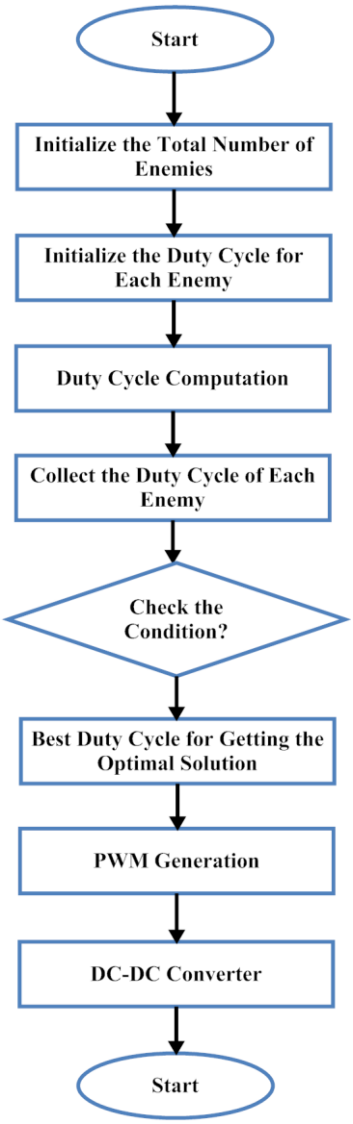


Fig 5. Flow of DC-DC Converter

The simulation illustration of the developed E2F algorithm is represented in Fig 4, and its corresponding flow is shown in Fig 5. The clear procedure of the proposed E2F algorithm for generating the PWM is illustrated as follows:

Algorithm I – Enemy to Friend Algorithm

Step 1: Initialize the enemies with anger;
Step 2: Initialize the reference;
Step 3: if previous power of PV panel > Current power of PV panel

$$Pmax = Previous\ power\ of\ panel$$

Else

$$D1 = eD1 + (V/reference)$$

This step is repeated for all the enemies;

Step 4: $V_m = 4.4 \times 10^{-6} \times (S - 638.25)^2 + 16.918 + 0.0504 \times (25 - T)$

Step 5: $I_m = 8.58 \times 10^{-3} \times S + (T - 25) \times 2.145 \times 10^{-5} \times S$

Step 6: $M = -3.0825 \times 10^{-11} 1.033 \times 10^{-7} S^2 - 1.9627 \times 10^{-4} S + 0.11683 + 2 \times 10^{-7} \times (25 - T)(S - 750)$

Step 7: $D = 1 - \sqrt{\frac{V_m}{I_m \times R_L}} - \frac{M}{\sqrt{R_L}}$

Step 8: Compare the duty cycle of enemies with D;
Step 9: Choose the duty cycle which is equal to D;
Step 10: Apply this final duty cycle to the switch of the DC to DC converter;

After initializing the total number of enemies, the duty cycle selection is performed as follows:

If D1 <= D
    D = D1;
Else if D2 <= D
    D = D2;
Else if D3 <= D

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        D = D3;
Else if D4 <= D
        D = D4;
Else if D5 <= D
        D = D5;
Else if D6 <= D
        D = D6;
Else
        D = D;
End if
```

F. Inverter

After optimization, the Indirect Sliding Mode Control (ISMC) is implemented to invert the output of converter. The ISMC is mainly employed to optimize the dynamics of inverter. It is an efficient and high frequency switching control that works based on the variable structure of control structure. It derives the system state based on the design of discontinuous control signal. For a grid connected DC-DC converter, it regulates both the active and reactive power. The major advantages of using ISMC are,

- Insensitive to parameter variations
- Increased robustness
- Reduced order compensated dynamics
- Finite time convergence,

4. Performance Analysis:

In this sector, the simulation results of both existing and proposed systems are evaluated and compared by using different performance measures such as output power, inverter output, MMPT power tracking, DC-DC converter output, three phase voltage, and line current. Table 1 shows the DC-DC converter specification of the proposed technique.

Table 1. DC-DC converter specification

Parameter	Values
Inductor (L)	7.3mH
Capacitor (C)	4400 πF
Switch	IGBT
Switch specification	
Internal resistance R_{on} (Ohms)	1e-3
Snubber resistance R_s (Ohms)	1e5
Snubber capacitance C_s (F)	inf
Diode Specification	
Resistance R_{on} (Ohms)	0.001
Inductance L_{on} (H)	0
Forward voltage Vf (V)	0.8
Initial current I_c (A)	0
Snubber resistance R_s (Chms)	500
Snubber capacitance C_s (F)	250e-9

G. DC to DC Converter Output

The output power of DC to DC converter is depicted in Fig 6, in which the power is estimated for both existing P&O and proposed techniques. In this graph, the pink color line denotes the existing method, and the yellow color denotes the proposed method. From this evaluation, it is observed that the output power of the proposed DC to DC converter is increased, when compared to the existing technique. Also, the output power is estimated with respect to varying temperature (T), and solar irradiance (G) values, which is represented in Table 2. Here, the value of temperature ranges from 20 to 40, and the solar irradiance is varied from 300, 500 and 1000. In this graph, the x-axis indicates the time in seconds, and the y-axis indicates the power in watts.

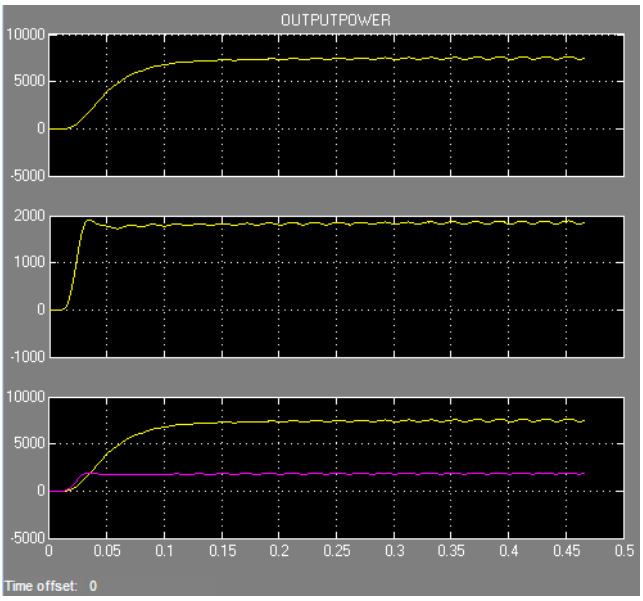


Fig 6. Output power of DC-DC Converter

Table 2. DC to DC converter output of both existing and proposed system

Temperature	Solar Irradiance	DC-DC converter output	
		Existing	Proposed
T = 20	G = 1000	42.72V	86.1V
T = 30	G = 1000	44.08V	88.68V
T = 40	G = 1000	45.31V	91.13V
T = 20	G = 500	40.81V	82.16V
T = 30	G = 500	42.1V	84.73V
T = 40	G = 500	43.33V	87.18V
T = 20	G = 300	39.49V	79.46V
T = 30	G = 300	40.79V	82.04V
T = 40	G = 300	42.02V	84.49V

Fig 7 shows the output voltage of DC-DC converter for both existing (P&O) and proposed techniques. In which, the voltage is estimated at constant temperature i.e. for 0s to 0.5s, the irradiance level is 1000W/m^2. Then for 0.5s to 1s, the irradiance level is 500 W/m^2 and 1s to 1.5s, the irradiance level is 1000 W/m^2 with respect to the temperature of 40°C.

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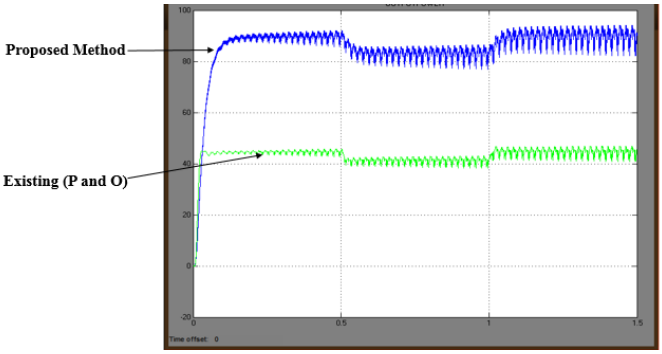


Fig 7. Output voltage of DC-DC converter

From the evaluation, it is observed that the proposed DC-DC converter outperforms the existing converter by efficiently generating the PWM based on an optimization process.

H. MPPT Power Tracking

The efficiency of power tracking by both existing and proposed techniques are shown in Fig 8 and Fig 9. In this analysis, the value of T is <= 0.03 at G = 1000, and T > 0.03 at G = 500 are considered for evaluating the efficiency of the power tracking techniques. In this simulation, it is proved that the proposed MPPT efficiently tracks the power from the solar panel, when compared to the existing technique.

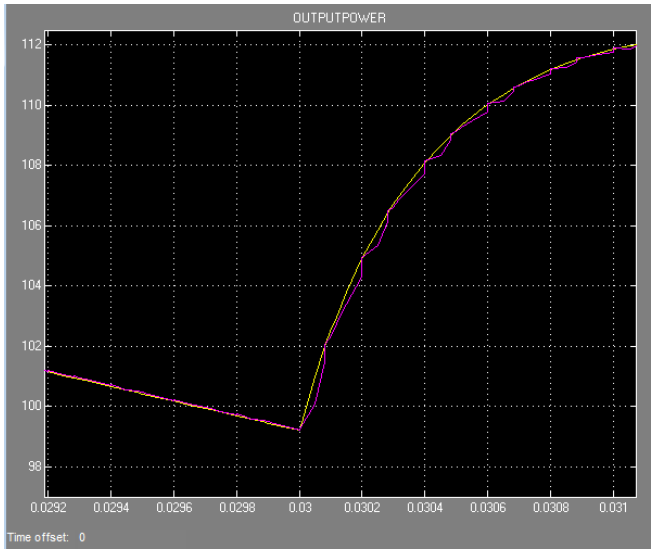


Fig 8. Power tracking of the existing technique

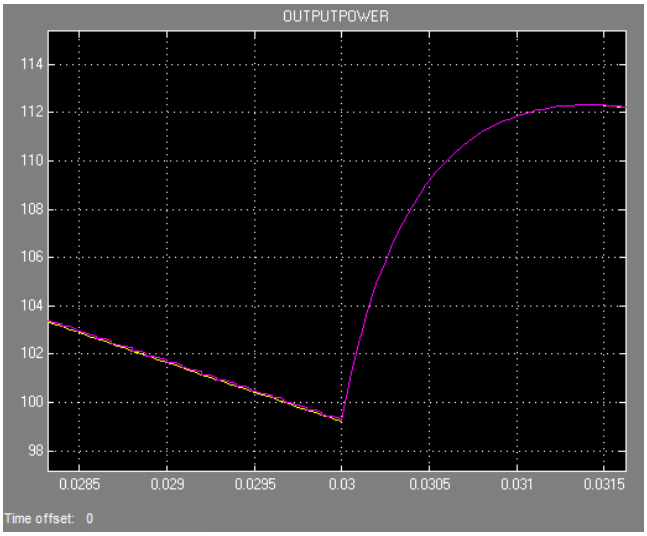


Fig 9. Power tracking of the proposed MPPT technique

I. Three Phase Voltage

The three phase voltage output of both existing and proposed techniques is depicted in Fig 10. In this simulation, it is evaluated based on the Point Common Coupling (PCC) that includes the meeting point of PV system, load and grid.

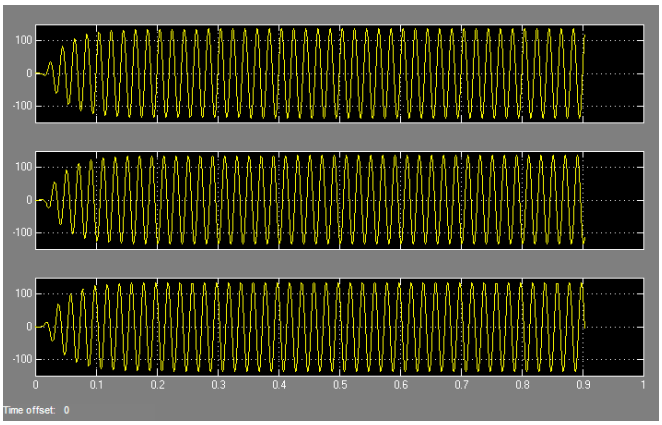


Fig 10. Three phase voltage of the existing method

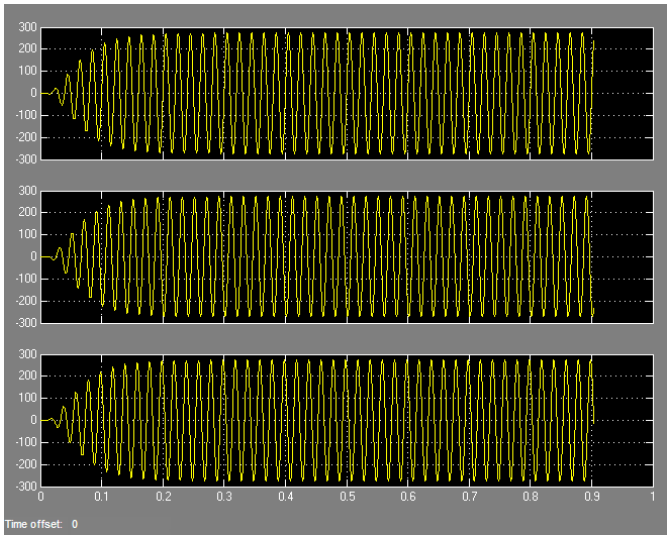


Fig 11. Three phase voltage of the proposed method

When compared to the existing technique, the proposed technique has the increased three phase voltage.

J. Line Current

Fig 12 shows the line current of the proposed system, in which there is no fluctuations in the line current at I_A, I_B and I_C. Normally, the line current is estimated based on its direct flow that is increased when the voltage is applied on the load. In this simulation, the peak current is sensed by correcting the duty cycle of the converter.

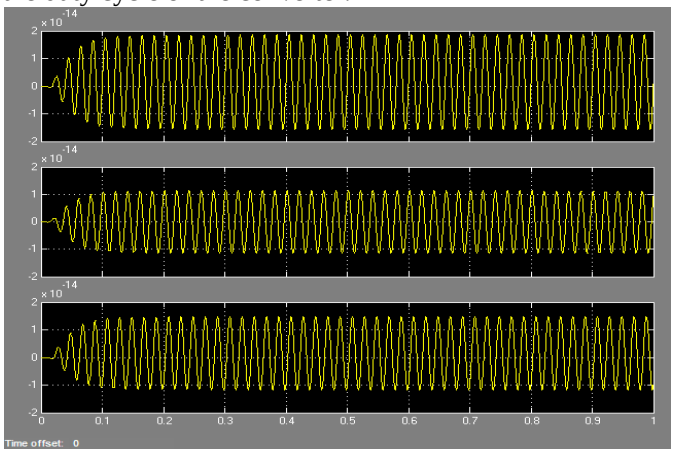


Fig 12. Line current

K. Inverter Output

The inverter of both existing P&O and proposed ISMC are shown in Fig 13 and Fig 14. Normally, the inverter output is increased with no fluctuations, so it can be used for the power system. Here, the inverter output is estimated for the three phase voltage, when compared to the existing inverter, the proposed output of the proposed ISMC is improved.

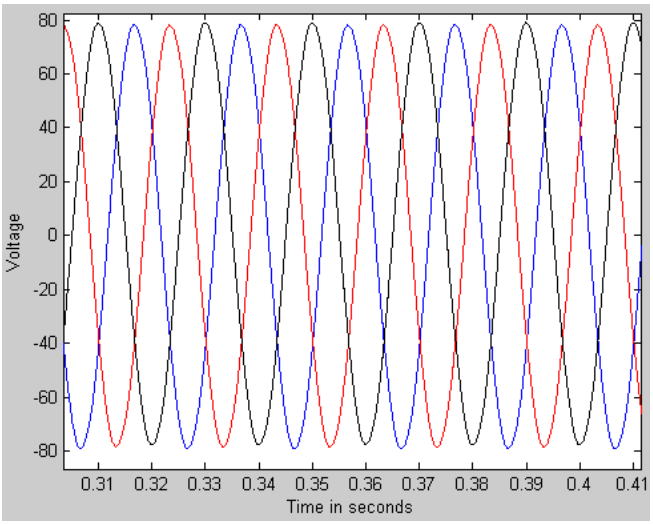


Fig 13. Inverter output of the existing (P&O) converter

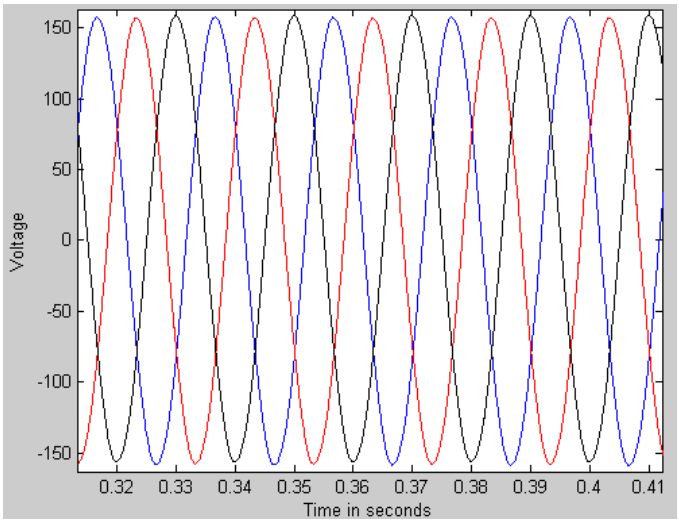


Fig 14. Inverter output voltage of the proposed ISMC

5. Conclusion and future work:

This work presents a new optimization based DC to DC converter design for a BIPV systems. Here, the changes that appeared in solar irradiance and temperature are observed by computing the duty cycle. For this purpose, a novel E2F based optimization technique is developed with MPPT for generating PWM. The solar irradiance is converted into an electrical energy with the use of DC to DC conversion. In the converter stage, the MPPT technique is implemented with E2F, which estimates the anger of each enemies. Then, the enemy who has the minimum anger is selected and made as a friend. Based on this process, the duty cycle of each enemy is computed, and the duty cycle that having the best value is selected for getting the optimal solution. Subsequently, the PWM is generated and the generated pulse are used for DC to DC conversion. After that, the controlling structure is implemented to invert the output of DC to DC converter by employing the ISMC technique. Finally, the

inverted output is connected for either microgrid or load. The major advantages that obtained by using E2F are, reduced power loss, increased efficiency, and better optimization. To evaluate the proposed controlling strategy, different performance measures are used during simulation. In order to prove the superiority of the proposed technique, it is compared with the existing methodology. From the evaluation, it is observed that the proposed E2F optimization based DC to DC converter outperforms the existing technique.

In the future work, the developed system will be improved by implementing the proposed system in a real time water pumping application. Also, the results will be improved by employing an efficient optimization technique.

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