

Efficiency Evaluation of Boost and LLC Resonant Converters for Solar Water Pumping Applications

Nagma Bee[†], Kishor Thakre, and Prateek Nigam, Non-members

ABSTRACT

This study examines the application of an isolated LLC resonant DC–DC converter in a standalone solar water pumping system (SWPS) and evaluates its performance relative to a conventional boost converter-based configuration. The proposed system incorporates PV power-dependent speed reference generation, PI-controlled DC-link voltage regulation, and scalar V/f control of an induction motor to ensure stable operation under fluctuating solar irradiance. A comprehensive model of the system is developed in MATLAB/Simulink and validated through real-time experimentation using an OPAL-RT 4510 hardware-in-the-loop (HIL) platform. The LLC converter is operated at a switching frequency of 10 kHz, while the motor operating frequency is adaptively varied between 0 and 50 Hz based on available PV power. Comparative stage-wise power flow and efficiency analyses are performed at irradiance levels of 1000, 500, and 300 W/m² for both converter topologies. The results demonstrate effective motor speed regulation without excessive current stress and confirm that the LLC-based system achieves soft-switching operation with an overall efficiency improvement of approximately 1–1.5% compared to the conventional boost converter. Although the LLC topology entails increased circuit complexity and component count, its reduced switching losses, lower thermal stress, and improved conversion efficiency highlight its suitability for high-performance and reliable solar water pumping applications.

Keywords: Solar Water Pumping System (SWPS), LLC Resonant Converter

1. INTRODUCTION

Solar Water Pumping Systems (SWPS) utilize solar photovoltaic (PV) energy to drive electric water pumps, providing a clean and fuel-free alternative to conventional diesel- or grid-powered pumping solutions [1], [2]. Due to their decentralized nature and low operational cost, SWPS have gained significant attention for agri-

cultural irrigation and rural water supply applications [3]–[5]. A typical PV-fed SWPS employs a DC–DC boost converter (BC) or interleaved boost converter (IBC) with Maximum Power Point Tracking (MPPT), followed by a voltage-source inverter (VSI) to drive the motor [6]–[8]. Although boost converters are widely used because of their simple structure and ease of control, their hard-switching operation results in increased switching losses, particularly at higher switching frequencies required for improved motor performance [9].

Resonant DC–DC converter topologies have emerged as promising alternatives for high-efficiency power conversion applications, especially where reduced switching losses and electromagnetic interference are desired [10]. Among these, the isolated LLC resonant converter offers zero-voltage switching (ZVS) and zero-current switching (ZCS), leading to lower losses, reduced device stress, and improved efficiency [11]–[12]. While LLC converters have been explored in PV-based systems [13], [14], [5], their application in standalone PV-fed SWPS remains limited due to design complexity, control challenges under wide irradiance variation, and concerns regarding cost and feasibility compared to conventional boost-based solutions. Motivated by these challenges, this paper investigates the feasibility and performance of an isolated LLC resonant DC–DC converter for a standalone PV-fed SWPS and presents a systematic comparison with the conventional boost converter topology. The proposed system is developed in MATLAB/Simulink and validated using a real-time hardware-in-the-loop (HIL) platform to assess both dynamic performance and energy-conversion efficiency. The main contributions of this paper are summarized as follows:

- A standalone solar water pumping system (SWPS) based on an isolated LLC resonant DC–DC converter is proposed and comparatively evaluated against a conventional boost converter topology, providing practical insights into efficiency improvement for PV-fed pumping applications.
- A systematic analytical design methodology for the LLC resonant tank circuit is presented, addressing wide PV input-voltage variations and pump load requirements inherent to standalone SWPS.
- A unified control strategy is developed, integrating MPPT-based speed reference generation, PI-based DC-link voltage regulation, and V/f control of an induction motor to ensure stable speed tracking and safe current operation under varying solar irradiance conditions.
- A detailed stage-wise power flow and efficiency

Manuscript received on October 25, 2025; revised on January 19, 2026; accepted on March 31, 2026. This paper was recommended by Associate Editor Chainarin Ekkaravardome.

The authors are with Department of Electrical Engineering at Rabindranath Tagore University, Bhopal.

[†]Corresponding author: nagmabee.2021@gmail.com

©2026 Author(s). This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 License. To view a copy of this license visit: <https://creativecommons.org/licenses/by-nc-nd/4.0/>.

Digital Object Identifier: 10.37936/ecti-ec.2026242.262052

analysis is conducted for both boost- and LLC-based SWPS configurations at multiple irradiance levels, enabling a fair and quantitative comparison of converter-level and overall system efficiencies.

2. DESCRIPTION OF PROPOSED DESIGN

Figure 1(a) shows the proposed SWPS design, which comprises five main components: a Solar Panel (SP), an LLC resonant converter with a High-Frequency Inverter (HFI), a Diode Bridge Rectifier (DBR), a Voltage Source Inverter (VSI), and a motor; in our case it's an Induction Motor (IM). Figure 1 (b) shows the conventional SWPS structure most common in industrial practices and also discussed in many articles like [15-16] for comparison. This configuration consists of a Solar Panel (SP), (BC), (VSI), and (IM).

The proposed SWPS is designed to drive a 2-kW induction motor (IM) for irrigation applications. The PV array is rated to deliver sufficient DC power under standard test conditions (STC) to meet the motor load requirement. The array sizing is carried out considering local irradiance conditions, derating factors, and a DC-link voltage compatible with the resonant converter. The specifications of SP and IM are provided in Table 1.

3. LLC RESONANT CONVERTER DESIGN

This section presents a step-by-step analytical design of the LLC resonant converter, including load reflection, resonant tank parameter selection, and gain analysis under wide PV input variation. Figure 2 (a) shows the LLC resonant converter topology [17]; this converter takes DC as input and provides regulated DC voltage at the output. Unlike other DC-DC converters, LLC topology is highly efficient due to negligible switching losses because of ZVS and ZCS operations at high frequencies; it is fast and mostly preferred in battery charging applications [18]-[19]. In this work, an LLC topology has to be designed that takes DC input from SP. The design should be such that the topology performs well in wide input variations, as we know the irradiance level may change depending upon the sun's position. The designing begins with the design of the tank circuit shown in Figure 2 (b) as an equivalent circuit; it is the reduced form of Figure 2 (a) formed by transferring the input side of the system, i.e., the solar PV input, and the output side, i.e., the motor with the pump load in the middle. For this, the output power delivered to the motor is converted into its equivalent resistance R_o shown in equation (1), which is then referred to the input side of the inverter. This resistance is further transferred to the input side of the DBR, where the resistance equivalent becomes R_{rl} , whose value is given in equation (4). This is obtained by following the input-output relations of the DBR circuit shown in equations (2-3).

$$R_o = \frac{V_o^2}{P_o} = \frac{V_o}{I_o} \quad (1)$$

$$V_i = \frac{4 \cdot V_o}{\pi} \quad (2)$$

$$I_i = \frac{\pi \cdot I_o}{2} \quad (3)$$

$$R_{rl} = \frac{V_i}{I_i} = \frac{8 \cdot V_o}{\pi^2 \cdot I_o} \quad (4)$$

Further R_{rl} is transferred to the input side of the transformer following the secondary to primary winding resistance shifting rule, where the resistance equivalent becomes R_{eff} expressed in equation (5), where n_1 and n_2 are the number of turns in the primary and secondary sides of the transformer.

$$R_{eff} = \frac{8}{\pi^2} \cdot R_L \left(\frac{n_1}{n_2} \right)^2 \quad (5)$$

The input is a high-frequency sinusoidal signal given as V_{ab} , and is generated from a full-bridge converter operating at 10 kHz. Once the output and input across the equivalent circuit are obtained, the parameters, i.e., resonant inductance L_r , magnetizing inductance L_m , resonant capacitance C_r and transformer design, are obtained through these known input and output parameters. Owing to the fact that lossless power transmission can be done if the ratio of output to input is unity, here $\frac{V_{pq}}{V_{ab}}$ is maintained to unity. The ratio of output voltage V_{pq} to the input voltage V_{ab} can be derived by solving the circuit in the Laplace domain; the final obtained equation is given as (6).

$$\frac{V_{pq}}{V_{ab}} = \frac{8}{p^2} \cdot \frac{X_{Lm}}{\sqrt{(X_{Lr} + X_{Lm} - X_{Cr})^2 + R_{eff}^2}} \quad (6)$$

The equation (6) consists of parameter information, hence X_{Lr} , X_{Lm} , and X_{Cr} are replaced with resonant inductance L_r , magnetizing inductance L_m and resonant capacitance C_r following equations (7-10) for the resonant frequency operation f_r , in our case of a 4 kW application, resonant frequency is considered equal to switching frequency, i.e., 10 kHz. The obtained parameters are further replaced in terms of the frequency ratio ω_x , the inductance ratio m , and the quality factor Q , utilizing equations (11-13) as the obtained unknown parameters for the circuit are self L_r , L_m , and C_r .

$$X_{Lr} = 2\pi f_r \cdot L_r \quad (7)$$

$$L_r = \frac{R_e \cdot Q}{2\pi f_r} \quad (8)$$

$$L_m = (m - 1) \cdot L_r \quad (9)$$

$$C_r = \frac{1}{L_r \cdot (2\pi f_r)^2} \quad (10)$$

$$\omega_x = \frac{\omega}{\omega_0} \quad (11)$$

$$m = \frac{L_r + L_m}{L_r} \quad (12)$$

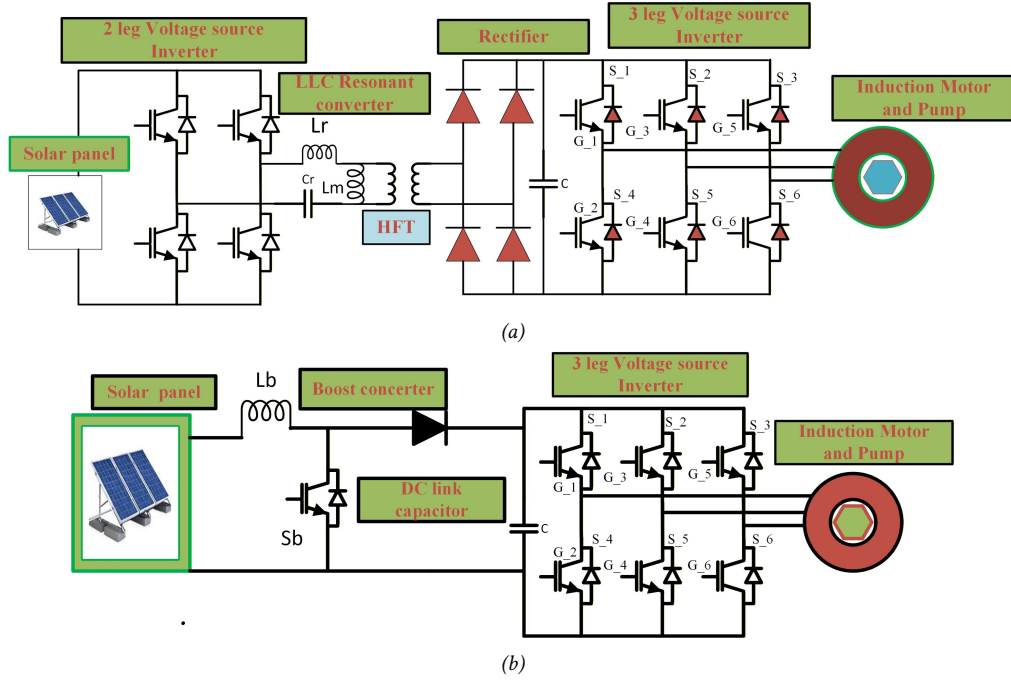


Fig. 1: SWPS system (a) with LLC (b) with BC.

Table 1: Key Specifications of Solar PV Array and Induction Motor.

(PV Array)	Specification	Parameter (IM)	Specification
Parallel Strings	1	Power (P), frequency	2200 VA, 50 Hz
Series String	11	Rated Voltage (V_{LL})	400 V
Maximum Power	224.76 W	Stator Resistance (R_s)	1.405 Ω
Array power	2472 W	Stator Inductance (L_{ls})	0.005839 H
Open Circuit Voltage (V_{oc})	41.79 V	Rotor Resistance (R_r)	1.395 Ω
Short Circuit Current (I_{sc})	7.13 A	Rotor Inductance (L_{lr})	0.005839 H
Voltage at MPP (V_{mp})	33.9 V	Mutual Inductance (L_m)	0.1722 H
Current at MPP (I_{mp})	6.63 A	Inertia (J)	0.0131 kg·m ²
		pole pairs (p)	2

$$Q = \frac{X_{L_r} - X_{C_r}}{R_{eff}} \quad (13)$$

The replacement in terms of ω_x , m and Q gives equation (14).

$$\frac{V_{pq}}{V_{ab}} = \frac{8}{p^2} \cdot \frac{\omega_x^2 \cdot (m-1)}{\sqrt{(m \cdot \omega_x^2 - 1)^2 + Q^2 \cdot \omega_x^2 \cdot (\omega_x^2 - 1)^2 \cdot (m-1)^2}} \quad (14)$$

For achieving the ratio of $\frac{V_{pq}}{V_{ab}}$ as unity, iterative analysis is performed for various quality factors Q and values of m using MATLAB script.

Finally, at $m = 7$ and $q = 0.6$, the curve with yellow color shown in Figure 3 provides a unity point. Therefore, for the 4-kW application, the resonant tank circuit parameters, i.e., resonant inductance L_r , magnetizing inductance L_m , resonant capacitance C_r , and transformer are obtained, and in Table 2, the values of these parameters are specified.

Table 2: Obtained LLC parameters.

Parameter	Symbol	Value
Transformer Turns Ratio	n	300/400
Load	R_o	5 kW, 400 V
Reflected Load Resistance	R_e	14.61 Ω
Resonant Inductance	L_r	148.77 μ H
Magnetizing Inductance	L_m	743.85 μ H
Resonant Capacitance	C_r	1.7026 μ F

4. LLC DRIVEN MOTOR CONTROL SETUP

In Figure 4, the control strategy for both the IGBTs of the LLC resonant converter (S1–S4) and the voltage source inverter (VSI, S₁–S₆) is illustrated. The primary

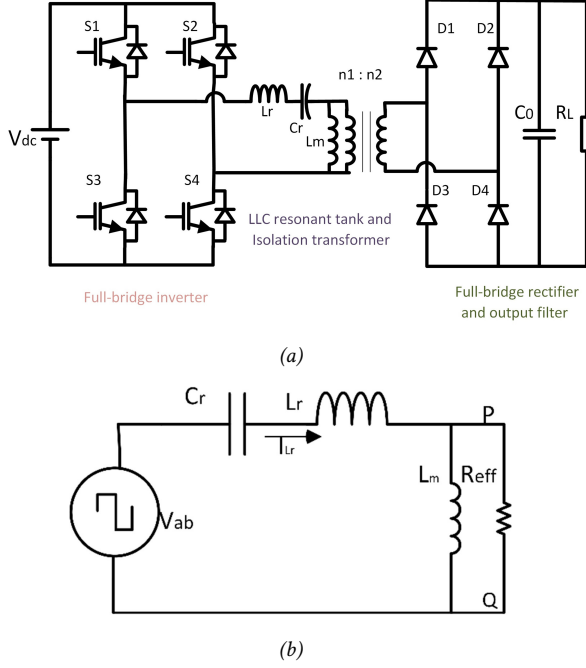


Fig. 2: (a) LLC Topology (b) Reduced Equivalent circuit.

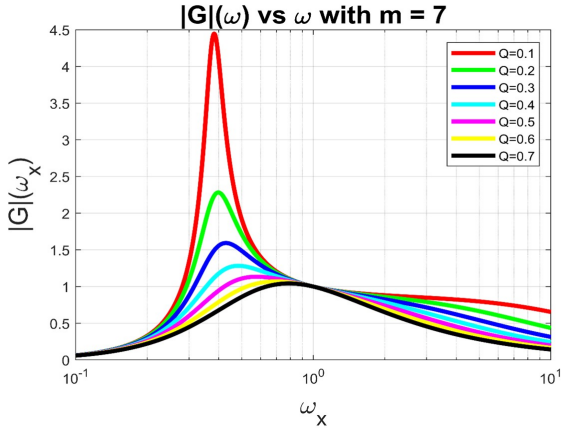


Fig. 3: Gain Vs frequency curve for $m=7$ at varying Q .

objective of this control scheme is twofold: to regulate the motor speed according to the available solar photovoltaic (SP) power and to maintain a stable DC-link voltage (V_{dc}).

The reference speed $\omega_{panelref}$ is first determined from the available SP power P_{PV} using the relation of equation (15) [7].

$$\omega_{panelref} = K_p 3\sqrt{P_{PV}} \quad (15)$$

Here K_p is the pump constant, which is determined through the pump affinity law, i.e., torque is directly proportional to the square of the speed; see equation (16).

$$T \propto N^2 \quad (16)$$

Therefore,

$$K_p = \frac{T}{N^2} \quad (17)$$

The obtained reference speed $\omega_{panelref}$ is compared with the actual motor speed ω_{actual} (shown in light blue in Figure 4), and the resulting error $e_\omega(t)$ shown in equation (18) is processed by a PI controller to generate the reference DC-link voltage $V_{dc,ref}$ required to achieve the desired speed, mathematically shown in equation (19), here $K_p^{(1)}$, and $K_i^{(1)}$ are the proportional and integral gains to achieve the desired response.

$$e_\omega(t) = \omega_{panelref} - \omega_{actual} \quad (18)$$

$$V_{dc,ref} = K_p^{(1)} e_\omega(t) + K_i^{(1)} \int_0^t e_\omega(\tau) d\tau \quad (19)$$

The reference DC-link voltage $V_{dc,ref}$ is compared with the measured DC-link voltage $V_{dc,measured}$ and the error e_{Vdc} shown in equation (20) is fed into a second PI controller that generates the switching frequency f_{LLC} for the LLC resonant converter mathematically shown in equation (21) where $K_p^{(2)}$ and $K_i^{(2)}$ are the proportional and integral gains of the second PI controller, respectively. The proportional gains of both the PI controllers are selected based on the ratio of output to input responses, while integral gains are selected on a trial-and-error basis.

$$e_{Vdc} = V_{dc,ref} - V_{dc,measured} \quad (20)$$

$$f_{LLC} = K_p^{(2)} e_{Vdc}(t) + K_i^{(2)} \int_0^t e_{Vdc}(\tau) d\tau \quad (21)$$

The generated switching frequency is multiplied by 2π and integrated to produce the position angle θ . Using θ and equation (22), PWM pulses are derived for the LLC switches (S1–S4).

$$c(\theta) = 0.5 \left(\frac{2}{\pi} \arcsin(\sin \theta) + 1 \right) \quad (22)$$

The equation (22) is a normalized control derived from the sinusoidal input. The inner term $\arcsin(\sin \theta)$ creates a piecewise-linear function that effectively maps the sinusoidal variation into a triangular-like shape. By scaling with $\frac{2}{\pi}$, the output is normalized to the range $[-1, 1]$, and the subsequent shift and scaling with $0.5(+1)$ transform it into the range $[0, 1]$. This makes the function suitable for modulation purposes, such as the generation of a duty cycle for the resonant inverter control.

The same switching frequency signal f_{LLC} is scaled by the gain G (50/10 kHz) to obtain the angular frequency of the motor. This angular frequency is integrated to obtain the desired rotor position θ_p . The modulation index M is then computed following equation (23). Finally, using both M and θ_p , V/f control is implemented in the motor drive following equation (??), here ϕ_x is the phase difference angles for the three phases of the motor and $v_x^*(t)$ is the instantaneous phase voltages for the three phases (x) $\in a, b, c$.

$$M = \frac{2\sqrt{2} V_{phase,rms}^*}{V_{dc}} * \frac{2\pi f_c}{100 * \pi} \quad (23)$$

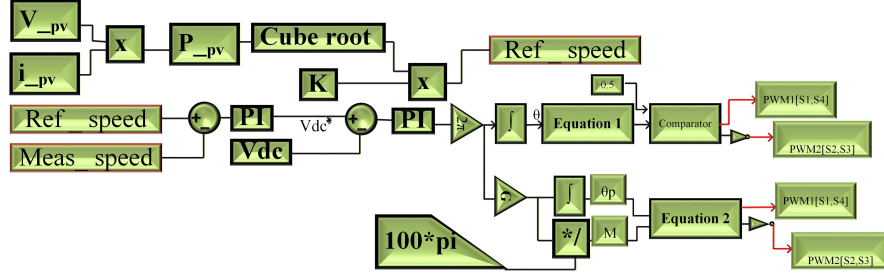
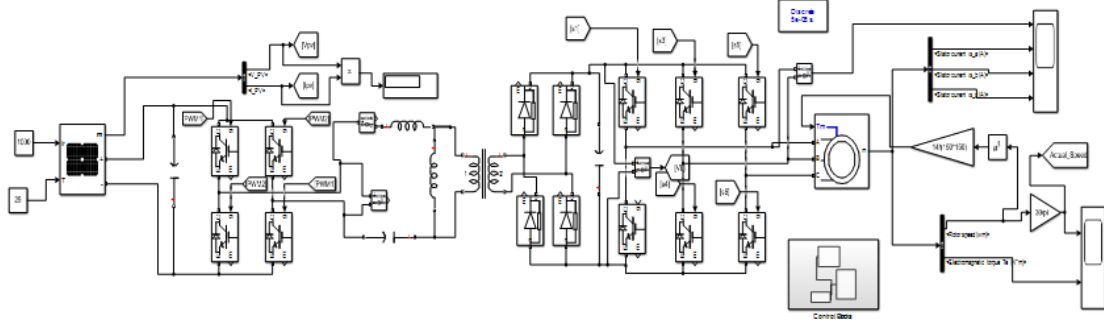
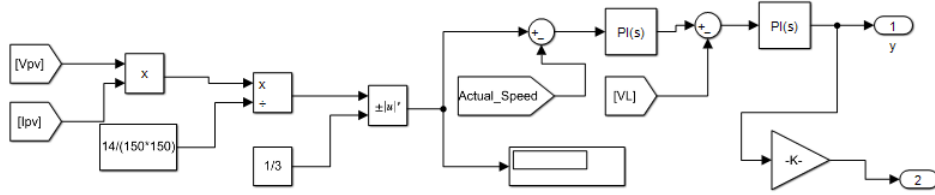


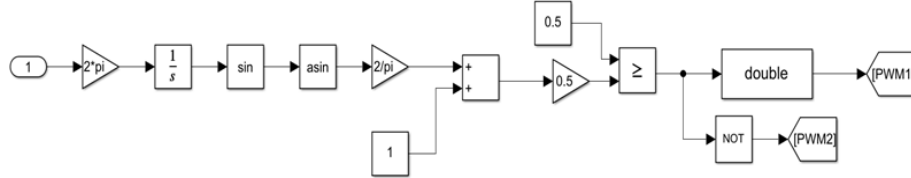
Fig. 4: Proposed Control Scheme.



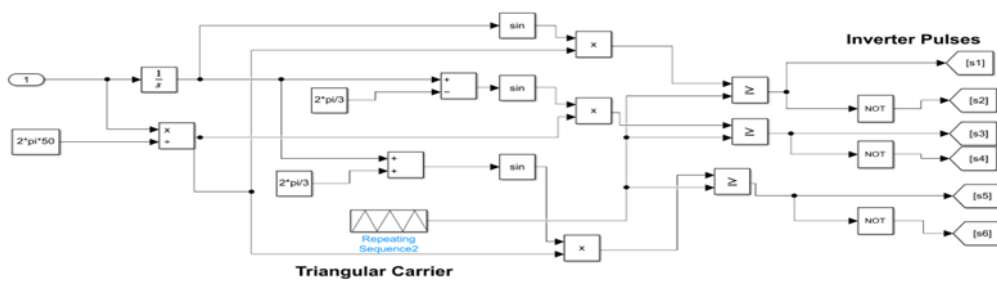
(a)



(b)



(c)



(d)

Fig. 5: MATLAB/Simulink implementation of the proposed SWPS: (a) overall system model, (b) reference speed estimation (c) LLC full-bridge inverter control, and (d) induction motor V/f control.

$$v_x^*(t) = \frac{1}{2} (1 + M \sin(\theta_p + \phi_x)) \quad (24)$$

where $\phi_x \in \{0, -120, 120\}$.

The constant Volt-per-Hertz (V/f) control is one of the simplest scalar control strategies for induction motors, where the supply voltage is adjusted proportionally with the operating frequency to maintain a nearly constant air

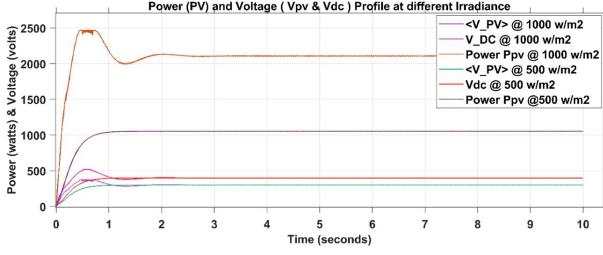


Fig. 6: Power and Voltage Profile at 1000 w/m^2 and 500 w/m^2 (obtained using Data Inspector MATLAB).

gap flux. By preserving the ratio V/f , the motor avoids saturation at low frequencies and ensures sufficient torque capability across the speed range. Although this method does not provide dynamic performance comparable to vector control, it is widely used in applications such as pumps, fans, and compressors due to its simplicity, reliability, and ease of implementation.

The cascaded PI-based control structure ensures smooth dynamic response by decoupling speed regulation and DC-link voltage control. The outer speed loop generates a reference DC-link voltage based on available PV power, while the inner loop dynamically adjusts the LLC switching frequency, ensuring fast disturbance rejection under irradiance variations.

5. SIMULATION, EXPERIMENTAL SETUP AND RESULT ANALYSIS

Figure 5 is showing 4 portions from 5 (a) to 5 (d); 5 (a) shows the complete LLC-operated SWPS shown in Fig. 1 (a), developed in MATLAB Simulink; 5 (b) shows the estimation process of reference speed as per available SP power that generates DC link voltage reference through the PI controller following equation (19). Following equation (21), another PI controller generates f_{LLC} , it is shown when Figure 5 (b) ends at output 1 (y), and this output 1 (y) is connected to input 1 of Figure 5 (c) with f_{LLC} generating PWM 1 and PWM 2 for LLC converter operation. The output 2 of Figure 5 (b) is passed to input 1 of Figure 5 (d) for speed control of IM through v/f control strategy expressed in detail in the in the explanation of equations (23) and (??), respectively.

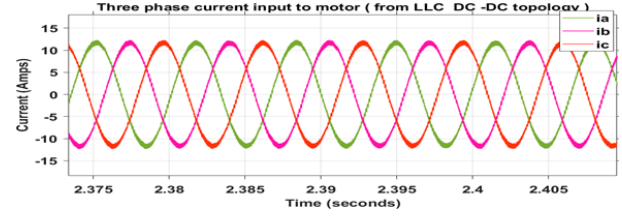
Figure 6 shows photovoltaic (PV) power, Voltage V_{pv} and DC link voltage V_{dc} at two different solar irradiance levels of 1000 W/m^2 and 500 W/m^2 . For better clarity and comparison, PV power and voltage profiles are shown in the same graph using Data Inspector in MATLAB/Simulink.

Although a dedicated MPPT algorithm is not explicitly implemented, the proposed control inherently ensures maximum power extraction by regulating DC-link voltage and motor speed according to available PV power.

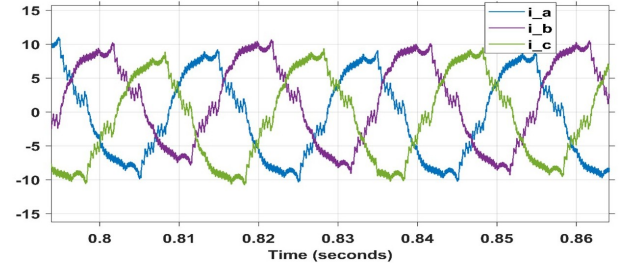
The voltage and power profile obtained through the designed control setup of Figure 4 resembles the same output as that tracked through maximum power point tracking (MPPT) methods in boost converter designs.



Fig. 7: Speed Profile at 1000 w/m^2 , 500 w/m^2 , 300 w/m^2 .



(a)



(b)

Fig. 8: Three Phase motor current (a) at 1000 w/m^2 (b) at 300 w/m^2 .

The close tracking of V_{dc} with V_{pv} confirms effective DC-link control and stable power transfer from the PV source under varying irradiance conditions through the proposed topology.

Further, the motor performance can be analyzed through speed tracking performance and the current profile. At irradiances (W/m^2) of 1000, 500, and 300, the speed of IM is captured and shown in figure 7. Again, for better clarity, the data inspector in MATLAB Simulink is used to fully show the speed performance from start to end of the simulation. No step response or slider gain is used for better encountering motor inertia. It can be seen in the results that the motor attains the reference speed generated by the available solar power in the developed topology for the irradiance of 1000, 500, and 300 W/m^2 , respectively, without exceeding the rated value of current; it rises slowly from zero to maximum as irradiance settles. In Figure 8 (a) and (b), the three-phase motor current profile from the inverter to the motor at 1000 w/m^2 and 300 w/m^2 is shown. It can be observed that at 300 w/m^2 the ripples in the current are increased, resulting in increased total harmonic distortion; however, at 1000 w/m^2 the proposed topology worked very fine.

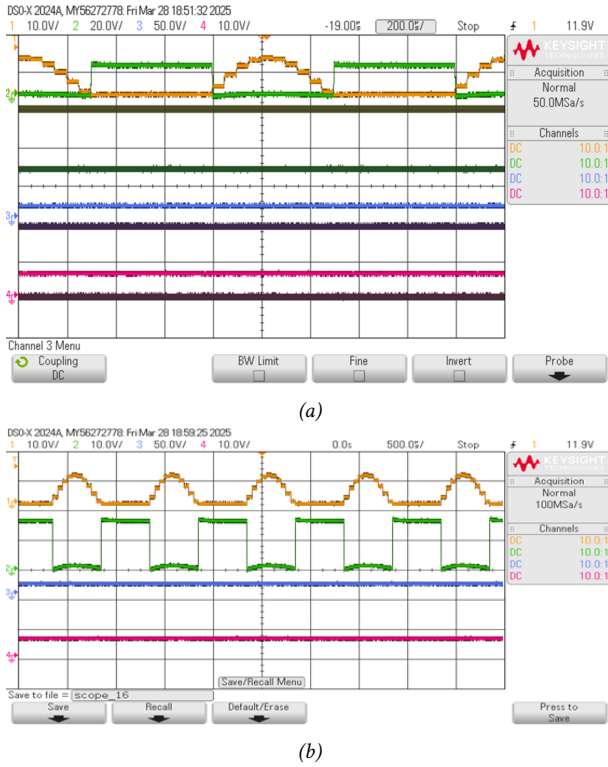
The experimental validation of obtained simulation

Table 3: Stagewise Power statistics for Boost Converter Assisted SWPS.

Irradiance (W/m ²)	PV Out (W)	Boost Out (W)	Inverter Out (W)	Motor Out (W)	Conv. Eff (%)	Inv. Eff (%)	Motor Eff (%)	Overall Eff (%)
1000	2468.90	2366.20	2296.80	2108.50	95.9	97.0	91.9	85.45
500	1232.40	1170.80	1125.60	1004.20	95.0	96.1	89.2	81.50
300	738.60	697.20	662.40	585.90	94.4	95.0	88.5	79.30

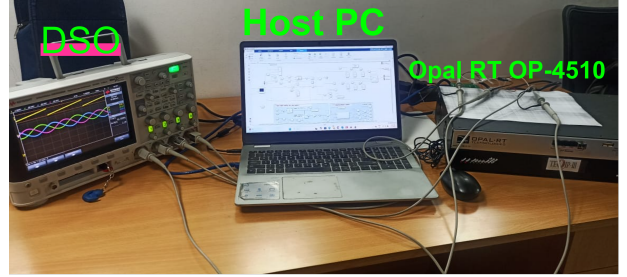
Table 4: Stagewise Power statistics for LLC Converter Assisted SWPS.

Irradiance (W/m ²)	PV Out (W)	LLC Out (W)	Inverter Out (W)	Motor Out (W)	Conv. Eff (%)	Inv. Eff (%)	Motor Eff (%)	Overall Eff (%)
1000	2469.80	2402.10	2294.50	2142.30	97.3	95.5	93.4	86.8
500	1231.90	1182.40	1134.20	1028.60	96.0	95.9	90.7	83.5
300	739.20	706.10	670.80	604.80	95.5	95.0	90.2	81.9

**Fig. 9:** Green is voltage & orange is current in IGBT, blue colour is steady state PV voltage V_{pv} , pink colour is DC link voltage V_{dc} (a) at 1000 w/m² (b) 500 w/m² .

results, especially zero voltage switching (ZVS) and zero current switching (ZCS) in IGBT switches of LLC topology, DC bus voltage, and PV power for 1000 w/m² and 500 w/m² at steady state, is shown in Figure 9. This validation is done through OPAL RT 4510, which is a real-time, hardware-in-loop (HIL) setup shown in Figure 10.

In the OPAL-RT 4510 HIL setup, control algorithms are executed in real time, while power-stage signals are appropriately scaled to comply with hardware voltage and current limits. The switching frequency handling

**Fig. 10:** OPAL -RT setup for HIL simulation.

and sampling time are selected to accurately emulate high-frequency LLC operation while ensuring numerical stability.

At this stage efficiency analysis of the two topologies is done, and results obtained of stagewise power obtained for boost converter-assisted SWPS and LLC topology-assisted SWPS are tabulated in tables 3 and 4, respectively. For this, at each stage, output power, i.e., PV input power, LLC converter output power, inverter output power, and motor output power for three different irradiances, is measured.

From the tabulated results, it is evident that both topologies exhibit proportional variation of output power with the available irradiance, as the PV input scales linearly with solar insolation. However, the LLC-assisted SWPS consistently demonstrates superior overall efficiency ($\approx 87\%$) compared to the boost-converter-assisted SWPS ($\approx 85\%$), owing to reduced switching losses enabled by the resonant operation. This efficiency margin, though modest, translates to reduced thermal stress, lower stage-wise losses, and improved utilization of available solar power, particularly at higher irradiance levels.

6. CONCLUSION

This work has presented a detailed comparative evaluation of boost- and LLC-resonant-converter-based solar water pumping systems using simulation and real-time

hardware-in-the-loop (HIL) validation. The developed control strategy, combining PI-based DC-link regulation with V/f induction motor drive, successfully enables motor speed tracking in proportion to available solar irradiance. The HIL results confirm that the LLC resonant converter achieves soft-switching operation and delivers higher overall system efficiency ($\approx 87.0\%$) compared to the conventional boost converter ($\approx 85.6\%$) across different irradiance levels.

Although the boost topology remains attractive for its simplicity, it suffers from increased switching losses under high-frequency operation. In contrast, the LLC topology offers reduced switching stress, lower power losses, and improved utilization of available solar energy, particularly under high irradiance conditions. While the LLC-based SWPS involves a higher component count and increased design complexity compared to the conventional boost converter, its soft-switching characteristics, reduced thermal stress, and enhanced efficiency make it a promising solution for long-term, efficient, and reliable solar water pumping applications.

REFERENCES

- [1] S. Murshid and B. Singh, "Implementation of PMSM Drive for a Solar Water Pumping System," *IEEE Transactions on Industry Applications*, vol. 55, no. 5, pp. 4956–4964, Sep. 2019.
- [2] S. Kudlur Thyagaraju, B. V. Reddy, and R. K. Jain, "A Direct Search Nelder Mead MPPT Based Induction Motor Drive for Solar PV Water Pumping System," *IEEE Transactions on Industry Applications*, vol. 61, no. 1, pp. 607–617, Jan. 2025.
- [3] J. Maurya, R. K. Saket, and R. K. Srivastava, "Performance Analysis of Single-Stage and Two-Stage VSI-Fed Induction Motor Drives for Solar Water Pumping Applications," *IEEE Transactions on Industry Applications*, vol. 60, no. 6, pp. 8856–8866, Nov. 2024.
- [4] H. Parveen and B. Singh, "PV Array Fed Synchronous Reluctance Motor Driven Water Pumping System with Grid Integration and Seamless Operability," *IEEE Transactions on Industry Applications*, vol. 60, no. 2, pp. 3724–3733, Mar. 2024.
- [5] S. Angadi, U. R. Yaragatti, Y. Suresh, and A. B. Raju, "Comprehensive review on solar, wind and hybrid wind-PV water pumping systems—an electrical engineering perspective," *CPSS Transactions on Power Electronics and Applications*, vol. 6, no. 1, pp. 1–19, Mar. 2021.
- [6] S. Shukla, B. Singh, P. Shaw, A. Al-Durra, T. H. M. El-Fouly, and E. F. El-Saadany, "A New Analytical MPPT-Based Induction Motor Drive for Solar PV Water Pumping System with Battery Backup," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 6, pp. 5768–5781, Jun. 2022.
- [7] M. Rezkallah, A. Chandra, M. Tremblay, and H. Ibrahim, "Experimental Implementation of an APC With Enhanced MPPT for Standalone Solar Photovoltaic Based Water Pumping Station," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 1, pp. 181–191, Jan. 2019.
- [8] B. Singh and M. Kashif, "PF-MRAC-Based Elimination of Sensors in Solar-Powered PMSM Drive-Based Water Pumping System," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 11, pp. 11390–11400, Nov. 2023.
- [9] A. K. Mishra, B. Singh, and T. Kim, "An Economical Solar Water Pump with Grid and Battery Backup for Continuous Operation," *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 4, no. 1, pp. 109–117, Jul. 2022.
- [10] M. Gasque *et al.*, "Energy Efficiency Optimization in Battery-Based Photovoltaic Pumping Schemes," *IEEE Access*, vol. 10, pp. 54064–54078, 2022.
- [11] H. Parveen, U. Sharma, and B. Singh, "Battery Supported Solar Water Pumping System with Adaptive Feed-Forward Current Estimation," *IEEE Transactions on Energy Conversion*, vol. 37, no. 3, pp. 1623–1633, Sep. 2022.
- [12] S. Haq *et al.*, "A Modified PWM Scheme to Improve the Power Quality of NPC Inverter Based Solar PV Fed Induction Motor Drive for Water Pumping," *IEEE Transactions on Industry Applications*, vol. 59, no. 3, pp. 3019–3030, May 2023.
- [13] J. Zeng, G. Zhang, S. S. Yu, B. Zhang, and Y. Zhang, "LLC resonant converter topologies and industrial applications—A review," *Chinese Journal of Electrical Engineering*, vol. 6, no. 3, pp. 73–84, Sep. 2020.
- [14] F. Alaql and I. Batarseh, "Review and Comparison of Resonant DC-DC Converters for Wide-Output Voltage Range Applications," in *Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 1197–1203, Oct. 2020.
- [15] D. Arnaudov, T. Todorova, and V. Dimitrov, "Study of LLC Resonant Converter with Multi-Transformer Topology," in *Proceedings of the 23rd International Symposium on Electrical Apparatus and Technologies (SIELA)*, 2024.
- [16] M. Pridala, M. Frivaldský, and S. J. Ovaska, "Comparison of LLC and LCCT converter topologies," in *Proceedings of the European Conference on Electrical Engineering and Computer Science (EECS)*, pp. 365–369, Jul. 2017.
- [17] J. Shahsevani and R. Beiranvand, "Application-Oriented Review of the LLC-Based Resonant Converters," *IEEE Access*, vol. 12, pp. 52687–52726, 2024.
- [18] N. Altin, S. Ozdemir, M. Khayamy, and A. Nasiri, "A Novel Topology for Solar PV Inverter Based on an LLC Resonant Converter with Optimal Frequency and Phase-Shift Control," *IEEE Transactions on Industry Applications*, vol. 58, no. 4, pp. 5042–5054, 2022.
- [19] A. Y. Farag, M. Rabah, K. A. El-Metwally, and A. Mahgoub, "Design Methodology of LLC Res-

onant Converter for PV-Powered Li-Ion Battery Charger,” *IEEE Access*, vol. 13, pp. 115640–115652, 2025.



Nagma Bee is currently pursuing a Ph.D. in Electrical Engineering under the Department of Electrical & Electronics Engineering at Rabindrabhat University, Bhopal. She holds a Master of Engineering degree with a specialization in Power System Engineering from LNCT collage, Bhopal. With experience as an Assistant Professor at RGPM College of Technology, Salaiya Bhopal, and Ravindra Nath Tagore University, Bhopal, Nagma has established herself as a dedicated academ-

ician. She has published research articles in reputable national and international journals. Her research interests include renewable energy and she has worked on various government projects related to Electrical Engineering and Renewable Energy. Some of her notable projects include Solar PV Installer (Suryamitra) and "Cost and Size Analysis of Hybrid System using Homer Optimization.



Kishor Thakre received his B.E. degree in Electrical and Electronics Engineering from RGPV Bhopal in 2007. He obtained his M.Tech. and Ph.D. degrees in Electrical Engineering from the National Institute of Technology Rourkela, India, in 2009 and 2019, respectively. He has published more than 50 research articles in reputed international journals and conference proceedings indexed in SCI, Scopus, and Web of Science. He actively serves as a reviewer for several

prestigious journals, including IEEE Transactions, IET Journals, IETES Wiley, IJE (Taylor & Francis), and various renowned Elsevier publications such as Renewable Energy, IJEPES, EPSR, and IAES Journal. Currently, he is working as an Associate Professor in the Department of Electrical Engineering at Rabindranath Tagore University, Bhopal. His research interests include multilevel inverters, with a particular focus on topology analysis and modeling of power electronic converters.



Prateek Nigam is currently working as an Associate Professor and Head in the Department of Electrical & Electronics Engineering in University Institute of Science & Technology, Rabindranath Tagore University, Raipur, Madhya Pradesh, India. He received his Master of Technology from the Department of Electrical Engineering (Specialization in Instrumentation Engineering), IIT Kharagpur, West Bengal, India and Ph.D. from Rabindranath Tagore University, Raipur, Madhya Pradesh, India. He is also a senior member of ISTE, IETE, IEEE, IAENG, ITEEA, IAER, AIIEA, IEDRC and IFERP. He wrote 10 books in various Electrical Engineering/Renewable Energy Fields. He is also having 14 Patents & many SCI/SCOPUS/WoS/Refereed indexed Research Articles in many reputed National/International Journals. His research interests include Renewable Energy, Measurement & Instrumentation, Wireless Communication and Power System Stability.

Madhya Pradesh, India. He is also a senior member of ISTE, IETE, IEEE, IAENG, ITEEA, IAER, AIIEA, IEDRC and IFERP. He wrote 10 books in various Electrical Engineering/Renewable Energy Fields. He is also having 14 Patents & many SCI/SCOPUS/WoS/Refereed indexed Research Articles in many reputed National/International Journals. His research interests include Renewable Energy, Measurement & Instrumentation, Wireless Communication and Power System Stability.