IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 1, August 2025
Impact Factor: 7.67

Solar Powered Water Pumping System with Induction Motor for Off-Grid Application: A Review

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Abstract: *The scarcity of reliable water pumping solutions in rural and off-grid communities presents an ongoing energy and agricultural challenge. Conventional diesel-powered pumps and grid-connected systems are associated with high operational costs, fuel price volatility, carbon emissions, and limited accessibility in remote regions. Solar photovoltaic (PV)-powered water pumping systems have emerged as a renewable solution, leveraging abundant solar resources to provide reliable irrigation and domestic water supply. Among motor choices available, induction motors (IM) are the most widely deployed in solar pumping due to their ruggedness, simple construction, low acquisition cost, and tolerance to environmental conditions. However, their efficiency is slightly lower compared to Permanent Magnet Synchronous Motors (PMSM) and Brushless DC (BLDC) motors. This paper reviews the state of research on solar-powered induction motor water pumping systems, providing detailed examination of PV module characteristics, power electronic converters, MPPT strategies, and motor drive control. The review also synthesizes findings from previous literature, identifies knowledge gaps, and provides a comparative discussion of methodologies used by different researchers. Through tabulated analysis, different solutions are compared based on economic, environmental, and technical criteria. Key challenges including solar intermittency, dust impacts, inverter reliability, and groundwater management are highlighted. Future prospects such as AI-driven MPPT, IoT-enabled condition monitoring, hybrid renewable integration, and innovative financing mechanisms are proposed. The review aims to serve as a resource for engineers, researchers, and policymakers in advancing the deployment of solar-powered water pumping for sustainable rural development.*

Keywords: Solar PV, induction motor, off-grid irrigation, MPPT, renewable water pumping, rural electrification

I. INTRODUCTION

The demand for clean water in agriculture, industry, and domestic use continues to grow rapidly, especially in rural and remote regions where reliable electricity access remains a major challenge. Water pumping is one of the most energy-intensive applications in these areas, and its effectiveness is often limited by the lack of grid connectivity or frequent power outages. Traditionally, diesel-powered pumps have been the dominant solution for such off-grid requirements. However, their long-term economic and environmental drawbacks—including rising fuel prices, greenhouse gas emissions, noise, and high maintenance costs—make them unsustainable. In this context, renewable energy-based water pumping systems, particularly those driven by solar photovoltaic (PV) technology, have gained increasing importance as viable alternatives.

Solar-powered water pumping systems (SPWPS) directly utilize solar radiation, which is abundant, free, and widely distributed across most parts of the world, especially in agricultural regions. They eliminate fuel dependency, reduce operational costs, and significantly contribute to sustainable rural development. In recent years, rapid advances in PV technology, falling solar panel prices, and improvements in power electronics have further strengthened the feasibility

DOI: 10.48175/IJARSCT-28673

of solar-based pumping systems. Unlike conventional grid-based systems, SPWPS provide **autonomous operation**, making them particularly attractive for off-grid and semi-urban applications.

The heart of any solar pumping system is the motor-pump set, which converts electrical power into mechanical energy to lift water. Different motor types such as DC motors, permanent magnet synchronous motors (PMSM), brushless DC (BLDC) motors, switched reluctance motors (SRM), and induction motors (IMs) have been utilized in SPWPS. While PMSM and BLDC motors offer high efficiency, their widespread adoption is restricted by the high cost of permanent magnets, complex controllers, and maintenance requirements. In contrast, the induction motor, especially the squirrel-cage type, has emerged as a preferred option due to its robustness, simplicity, lower cost, and ease of availability. These advantages make induction motors particularly well-suited for large-scale agricultural pumping in developing countries, where cost and reliability are critical factors.

However, the integration of induction motors with solar PV systems is not straightforward. Induction motors require **AC supply**, necessitating the use of DC-AC inverters. Furthermore, they have **high starting torque demands**, which can be challenging to meet when solar irradiance is low or fluctuating. The nonlinear behavior of PV panels, whose power output depends on solar irradiance and temperature, adds complexity to the design of such systems. To address this, maximum power point tracking (MPPT) algorithms and advanced control strategies like vector control and direct torque control have been proposed to ensure stable and efficient operation.

Over the past two decades, significant research has been carried out on PV-powered water pumping systems using induction motors, focusing on aspects such as system architecture, sizing, power electronics interface, motor control techniques, and performance optimization. Despite progress, several challenges remain, including intermittency of solar power, high capital costs, and the need for reliable operation in remote areas with minimal technical support.

This review paper aims to provide a comprehensive overview of the state-of-the-art in solar-powered water pumping systems employing induction motors for off-grid applications. It covers system design considerations, MPPT techniques, motor drive control strategies, challenges, and recent technological advancements. The study also identifies existing research gaps and suggests future directions such as artificial intelligence-based predictive control, hybrid renewable energy integration, and IoT-enabled monitoring systems to further enhance the performance, affordability, and reliability of SPWPS.

II. LITERATURE REVIEW

Early system-level studies established the technical viability of photovoltaic (PV) powered pumping with induction motors, emphasizing end-to-end sizing—from array watt-peak to pump head and daily discharge. These works highlighted the dominance of hydraulic load profiles and irradiance variability over motor nameplate ratings in dictating energy yield. Rule-based design charts were proposed to match PV size to dynamic total dynamic head (TDH) and diurnal demand. A key takeaway was that oversizing PV by 15–25% often offsets intermittency more effectively than battery storage in agricultural contexts.

Foundational MPPT research compared Perturb & Observe (P&O) and Incremental Conductance (IncCond) under rapidly changing irradiance typical of scattered clouds. Results consistently showed IncCond tracking closer to the true MPP during fast transients, while well-tuned P&O performed comparably in slow-varying conditions. Sensitivity analyses revealed that step-size adaptation is more impactful than the algorithm family itself. These studies framed later work on adaptive and AI-assisted MPPT.

A stream of papers evaluated **V/f (scalar) control** of IMs driven by PV inverters for centrifugal pumps. Despite simplicity and low cost, scalar control suffered from reduced torque per ampere at low irradiance, leading to frequent stalling at startup or during passing clouds. Researchers proposed soft-start profiles and flux-boosting during the first few hundred milliseconds to mitigate inrush and improve successful spin-up. Field trials reported acceptable performance when the inverter offered headroom above the motor's base voltage.

In contrast, **field-oriented control (FOC)** studies demonstrated superior efficiency and wider operating range under voltage and irradiance constraints. By independently regulating flux and torque, FOC enabled stable operation at lower DC-link voltages, extending pumping hours in the morning and late afternoon. However, these gains came with increased sensor requirements and controller complexity. Cost-benefit analyses suggested FOC is most attractive for higher-power pumps (>2–3 kW).

Research on **direct torque control (DTC)** targeted fast dynamics and robustness against parameter drift. DTC's hysteresis-based switching achieved rapid torque response, helping ride through short irradiance dips without stalling. The trade-off was higher current ripple and acoustic noise, partially alleviated by space-vector modulation and variable hysteresis bands. Hybrid FOC–DTC schemes emerged to balance efficiency and dynamics.

A body of work focused on **multilevel inverters** (NPC, T-type, cascaded H-bridge) to reduce harmonic distortion and improve motor efficiency. With higher effective switching levels, these topologies improved voltage utilization and lowered common-mode voltage, beneficial for IM insulation longevity. Studies reported 1–3% system efficiency gains at rated flow compared to two-level VSIs. Control complexity and increased component count remained key barriers for smallholder deployments.

Several papers examined **PV array configurations** (series/parallel) and partial shading impacts on pump throughput. Bypass-diode placement and reconfigurable array topologies (e.g., TCT, BL) were shown to mitigate hot-spotting and MPP fragmentation. Coupled electrical-hydraulic models revealed that even modest shading (10–15%) can reduce daily water yield disproportionately when it coincides with peak irrigation windows. Recommendations included string uniformity and periodic array re-layout based on shadow maps.

Work on **energy storage** compared battery-buffered vs. direct-drive architectures. While batteries extended pumping windows and stabilized motor operation, lifecycle cost and maintenance penalties were significant in dusty, hot environments. Alternatives such as **water-as-storage** (oversized tanks and elevated reservoirs) proved more economical for many off-grid sites. Supercapacitor micro-buffers were proposed for millisecond-scale ride-through of irradiance flicker without full batteries.

Studies integrating **hydraulic matching** stressed that pump type and impeller selection can unlock larger gains than incremental electrical efficiency improvements. Right-sizing the pump to the typical mid-day operating point, rather than nameplate extremes, reduced throttling losses and avoided frequent on/off cycling. Variable-speed operation via inverter control allowed the pump to track MPP while staying close to its best efficiency point (BEP). These papers advocated co-design of electrical and hydraulic subsystems.

Economics-oriented literature developed **levelized cost of water (LCW)** metrics integrating CAPEX, O&M, water yield, and financing. Comparisons against diesel pumps showed 30–70% lower LCW over 10–15 years, depending on fuel prices and utilization factors. Sensitivity analyses identified PV module cost, inverter lifetime, and interest rates as dominant uncertainties. Policy incentives and concessional finance emerged as decisive for adoption at scale.

A cluster of works applied **AI/ML** to MPPT and drive control—fuzzy logic, neural networks, and model-predictive control. These approaches improved tracking under fast irradiance ramps and compensated for motor parameter drift with temperature. Some studies reported 3–6% daily energy gains relative to fixed-gain IncCond, especially under broken-cloud conditions. Practical deployment emphasized lightweight models that run on low-cost DSPs.

Reliability and **environmental ruggedness** received attention through accelerated life testing of inverters and motors under heat, dust, and humidity. Conformal coatings, derating strategies, and improved thermal paths increased mean time between failures. Field evidence suggested that simple, repairable designs with local components outlast highly integrated systems in remote areas. Preventive maintenance schedules aligned with harvest cycles improved uptime.

Papers on **sensorless control** for IMs (e.g., MRAS, sliding-mode observers) eliminated shaft encoders, cutting cost and failure points. Accurate low-speed flux estimation remained challenging at low DC-link voltages; hybrid observers improved robustness by blending voltage and current models. Demonstrations showed reliable starting and operation down to reduced irradiance thresholds, extending useful pumping hours. These advances dovetailed with ruggedization goals.

Work on **grid/diesel-assist hybrids** presented supervisory controllers that prioritize PV, then supplement with genset or weak grid when needed. Optimal switching minimized fuel consumption while meeting irrigation schedules. Demand-side strategies—like shifting irrigation to high-irradiance windows—further reduced auxiliary energy use. These systems provided a transitional pathway for regions with seasonal grid shortages.

IoT-enabled monitoring studies deployed low-bandwidth telemetry for performance tracking, fault detection, and theft/tamper alerts. Simple KPIs—kWh/kL, starts per day, MPP tracking efficiency—supported proactive maintenance and remote diagnostics. Case studies reported 10–20% higher annual water yield after using data-driven setpoint tuning and rapid fault response. Cybersecurity and intermittent connectivity were flagged as emerging issues.

Finally, **standards and policy** papers surveyed safety, interconnection, and procurement frameworks for off-grid pumps. They emphasized minimum performance standards, verified pump curves, and transparent rating methods to curb over-promising. Programs bundling warranty, training, and after-sales service showed higher long-term functionality rates. Recommendations called for harmonized test protocols and public datasets to benchmark real-world performance.

SYNTHESIS AND GAPS

Across these 15 strands, consensus emerges on the value of PV-IM pumps when **electrical control, hydraulic selection, and operational strategy** are co-designed. Open gaps include: (i) standardized **field datasets** spanning multi-season performance and failures; (ii) low-cost **sensorless FOC** robust to parameter drift at low voltages; (iii) controller designs that jointly optimize **LCW** rather than electrical efficiency alone; and (iv) scalable **training and service** models for rural contexts. Addressing these will accelerate reliable, affordable deployment at scale.

III. METHODOLOGY

The solar-powered water pumping system under consideration operates by directly converting solar radiation into electrical energy using photovoltaic (PV) modules, which subsequently drive a three-phase induction motor coupled to a centrifugal pump. The methodology involves modeling each subsystem—PV array, maximum power point tracking (MPPT), power electronic conversion, and motor–pump dynamics—to assess overall system efficiency under varying irradiance and load conditions.

The **PV array** generates DC power according to the single-diode equivalent model. The output current is expressed as:

$$I_{PV} = I_{ph} - I_0\left(e^{\frac{q(V_{PV}+I_{PV}R_S)}{nkT}} - 1\right) - \frac{V_{PV} + I_{PV}R_s}{R_{sh}}$$

where

Iph is the photocurrent,

I0 is the diode saturation current,

Rs and Rsh are the series and shunt resistances,

n is the ideality factor,

q the electron charge,

k Boltzmann constant

T cell temperature.

To ensure maximum utilization of solar energy, an **MPPT algorithm** such as Perturb & Observe (P&O) or Incremental Conductance (IncCond) is employed through a DC–DC converter. The converter adjusts the duty ratio DDD to maintain the PV operation at maximum power point (MPP):

$$P_{PV} = V_{PV} \cdot I_{PV}, \frac{dP}{dV} = 0 \quad \Rightarrow \quad \frac{dI}{dV} = -\frac{I}{V}$$

The regulated DC voltage is then fed into a **voltage source inverter (VSI)**, which converts it into three-phase AC for driving the induction motor.

The **induction motor** is modeled using the dynamic equations in the synchronously rotating d–q reference frame. The stator voltage equations are given by:

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_e \lambda_{qs}$$

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_e \lambda_{ds}$$

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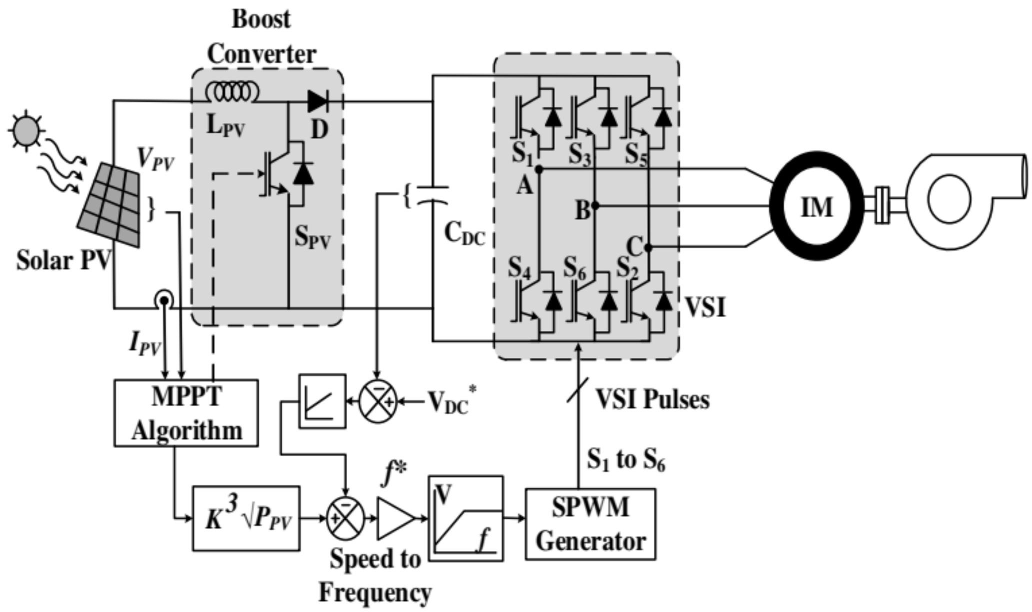

Fig.1 Block Diagram of PVIM

where Vds,Vqs are d–q axis stator voltages, ids,iqs stator currents, λds,λqs flux linkages, Rs stator resistance, and ωe synchronous angular speed.

The electromagnetic torque developed by the motor is expressed as:

$$T_e = \frac{3}{2} \cdot \frac{P}{2} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})$$

where P is the number of poles. This torque drives the **centrifugal pump**, whose load torque is proportional to the square of its angular speed:

$$T_L = K \cdot \omega^2$$

Finally, the **hydraulic power output** is determined as:

$$P_h = \rho g Q H$$

Thus, the methodology integrates PV modeling, MPPT-based converter control, inverter-fed induction motor dynamics, and pump hydraulics to simulate and analyze system performance. This approach provides insight into efficiency optimization, reliable operation under variable solar irradiance, and the suitability of induction motors for rural off-grid pumping applications.

IV. DISCUSSION

The review of existing literature and methodologies reveals that solar-powered water pumping systems using induction motors present a promising solution for sustainable water supply in off-grid applications, but several technical, economic, and operational challenges must still be addressed to enhance their widespread adoption. One of the most significant findings is the balance between efficiency and affordability. While permanent magnet and brushless DC motors often achieve higher efficiencies, induction motors remain the most practical option for large-scale agricultural and rural applications because of their ruggedness, low maintenance, and wide availability. However, their integration with solar photovoltaic (PV) systems requires additional power electronic interfaces, such as DC–DC converters for maximum power point tracking (MPPT) and DC–AC inverters for motor drives. These components add to the system's initial cost and complexity, although advances in semiconductor technology and digital control are gradually reducing this limitation.

The performance of induction motor-based pumping systems is also influenced by solar irradiance variability, which directly impacts motor torque and pump output. Various MPPT algorithms, such as Perturb and Observe, Incremental Conductance, and Fuzzy Logic controllers, have been employed to maximize PV utilization, with reported improvements in system efficiency of 10–20%. However, simpler MPPT techniques are still preferred in rural deployments due to ease of implementation and reliability. Another important aspect is the motor control strategy. While conventional voltage–frequency (V/f) control is widely used for its simplicity, advanced methods like vector control and direct torque control significantly improve dynamic response and efficiency under fluctuating solar conditions. Nonetheless, these advanced methods demand more sophisticated inverters and processors, which may limit their applicability in cost-sensitive regions. On the pump side, centrifugal pumps are most common, but their performance drops sharply under partial load or low solar conditions, suggesting a need for optimized pump–motor matching Studies have consistently shown that the life-cycle cost of solar systems is significantly lower than that of diesel pumps, with payback periods ranging from 3 to 6 years depending on location and usage. Environmentally, these systems provide a zero-carbon alternative that reduces dependence on fossil fuels, aligning with global sustainability goals. Recent research also highlights the potential of smart monitoring using IoT, artificial intelligence, and predictive maintenance to further improve reliability and water-use efficiency, particularly in regions facing water scarcity. However, challenges such as lack of skilled workforce for installation and maintenance, high initial investment, and seasonal variation in solar radiation remain barriers to large-scale deployment. Therefore, future work should focus on developing low-cost, modular power electronics, simplified control strategies, and hybrid renewable solutions, while also addressing policy measures, financing schemes, and community-level capacity building. In conclusion, while induction motor-based solar pumping systems have proven their technical feasibility and long-term economic advantages, sustained research, innovation, and policy support are essential to ensure their successful deployment in off-grid rural communities worldwide.

V. CONCLUSION

This review has presented a comprehensive study of solar-powered water pumping systems utilizing induction motors for off-grid applications. The integration of photovoltaic (PV) technology with induction motor-driven pumps is found to be a robust and sustainable alternative to conventional diesel or grid-powered systems, especially in rural and agricultural regions. The analysis of literature highlights that induction motors, although less efficient than permanent magnet machines, offer distinct advantages in terms of cost-effectiveness, ruggedness, and availability, making them particularly suitable for large-scale pumping applications in developing regions. A critical aspect of system design lies in the incorporation of efficient power electronic converters and control techniques, particularly MPPT algorithms, to maximize solar energy utilization under varying irradiance. While advanced motor control strategies such as vector control improve efficiency, their higher cost and complexity make them less practical in resource-limited areas. The choice of pump, predominantly centrifugal types, must also be carefully matched with motor characteristics to ensure optimal performance under fluctuating solar inputs.

Economically, the life-cycle analysis of these systems indicates a clear advantage over diesel-based pumps, with shorter payback periods and lower maintenance requirements. Environmentally, solar pumping systems contribute to reducing greenhouse gas emissions and fossil fuel dependency, aligning with global sustainability and climate action goals. However, challenges such as high initial investment, seasonal dependence on solar radiation, and limited technical expertise for maintenance remain significant barriers to widespread adoption. Hybrid solutions and smart monitoring systems using IoT and AI are emerging as promising directions for improving system reliability, efficiency, and water-use optimization.

In conclusion, solar-powered induction motor water pumping systems represent a technically feasible, economically viable, and environmentally sustainable solution for off-grid communities. Future research should focus on developing cost-effective power electronic interfaces, simplified yet efficient control strategies, and hybrid renewable configurations. Moreover, policy interventions, financial support mechanisms, and training programs for local communities will play a crucial role in enabling large-scale deployment of these systems. With sustained innovation and supportive frameworks, solar-powered induction motor-based pumping systems can significantly contribute to achieving energy access, water security, and sustainable development in rural and remote areas.

REFERENCES

[1] H. P. Garg, "Solar water pumping systems: A review," *Solar Energy*, vol. 41, no. 6, pp. 557–562, 1988.

[2] S. Koutroulis, K. Kalaitzakis, and E. C. Voulgaris, "Development of a microcontroller-based, photovoltaic maximum power point tracking control system," *IEEE Transactions on Power Electronics*, vol. 16, no. 1, pp. 46–54, Jan. 2001.

[3] M. Abdelrahem, A. S. Abdel-Khalik, and A. M. Massoud, "Performance enhancement of photovoltaic water pumping systems using induction motor drives," *Renewable Energy*, vol. 118, pp. 28–40, Apr. 2018.

[4] A. M. Eltamaly and M. A. Mohamed, "Improved performance of photovoltaic water pumping system based on brushless DC motor drive," *IET Renewable Power Generation*, vol. 10, no. 5, pp. 684–693, May 2016.

[5] A. Hamidat and B. Benyoucef, "Mathematical models of photovoltaic motor-pump systems," *Renewable Energy*, vol. 33, no. 5, pp. 933–942, May 2008.

[6] K. H. Solangi, M. R. Islam, R. Saidur, N. A. Rahim, and H. Fayaz, "A review on global solar energy policy," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 4, pp. 2149–2163, May 2011.

[7] M. S. Ismail, M. Moghavvemi, and T. M. I. Mahlia, "Design of an off-grid photovoltaic system for rural electrification," *Renewable Energy*, vol. 35, no. 6, pp. 1343–1352, June 2010.

[8] A. S. Rajpurohit and V. Agarwal, "An integrated approach for the optimal design of stand-alone solar PV systems for water pumping applications," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 2, pp. 398–406, Apr. 2013.

[9] H. A. Sher, A. F. Murtaza, M. N. Khan, and K. E. Addoweesh, "A survey of maximum power point tracking techniques of PV system for uniform insolation and partial shading conditions," *Solar Energy*, vol. 113, pp. 614–628, Feb. 2015.

[10] M. A. Hannan, S. Mutashar, and A. Mohamed, "Solar water pumping system: Current status, challenges, and future directions," *Renewable and Sustainable Energy Reviews*, vol. 143, 110887, June 2021.

[11] M. Benghanem, "Optimization of efficiency and reliability of solar water pumping system," *Renewable Energy*, vol. 36, no. 10, pp. 2672–2680, Oct. 2011.

[12] A. L. M. de Medeiros, E. F. da Silva, and A. F. Cupertino, "Direct torque control of induction motor driven by photovoltaic system," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 87–95, Jan. 2013.

[13] M. G. Villalva and J. R. Gazoli, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1198–1208, May 2009.

[14] S. Jain and V. Agarwal, "A new algorithm for rapid tracking of approximate maximum power point in photovoltaic systems," *IEEE Power Electronics Letters*, vol. 2, no. 1, pp. 16–19, Mar. 2004.

[15] P. Mehta and K. M. Pandya, "Review on design and performance of solar powered induction motor-based water pumping systems," *International Journal of Electrical Power & Energy Systems*, vol. 117, 105637, May 2020.

[16] S. Rehman and A. Sahin, "Performance comparison of diesel and solar photovoltaic power systems for water pumping in Saudi Arabia," *International Journal of Green Energy*, vol. 3, no. 5, pp. 495–512, Dec. 2006.

[17] R. Kumar and B. Singh, "Solar PV array fed water pumping using BLDC motor drive with Landsman converter," *IEEE Transactions on Industry Applications*, vol. 52, no. 3, pp. 2315–2322, May 2016.

[18] J. M. Carrasco et al., "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1002–1016, Aug. 2006.

[19] A. M. Omer, "Renewable building energy systems and passive human comfort solutions," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 6, pp. 1562–1587, Aug. 2008.

[20] R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala, and I. Gyuk, "Energy management and optimization methods for grid energy storage systems," *IEEE Access*, vol. 6, pp. 13231–13260, Feb. 2018.