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Control Strategy for Ensuring Uninterrupted Operation of a Solar Water Pump with Islanding Technique

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Abstract: - This research explores strategies to bolster the resilience of solar water pump systems through the implementation of islanding techniques and seamless grid integration. In the face of increasingly dynamic energy landscapes, the need for reliable and adaptable solutions for water pumping is paramount. The study investigates the application of islanding techniques, focusing on their effectiveness in enhancing system resilience and ensuring uninterrupted water supply. Furthermore, the integration of these solar water pumps with the grid is examined, aiming to strike a harmonious balance between renewable energy utilization and grid connectivity. The findings contribute to the advancement of sustainable water pumping technologies, offering insights into the synergy of islanding techniques and grid integration for resilient solar-powered water pump systems.

Keywords: Resilience;Islanding Technique;Solar Water Pumps;Grid Integration;Renewable Energy

I. INTRODUCTION

The utilization of solar photovoltaic (PV) technology in water pumping systems has garnered significant attention in recent years, presenting a promising avenue for sustainable solutions in vital sectors such as agricultural irrigation and community drinking water supplies. This introduction draws upon seminal works in the field to provide a comprehensive overview of the evolving landscape of solar PV water pumping systems. Researcher laid the foundation by extensively exploring the technical aspects, design considerations, and operational parameters of solar PV water pumping, with a specific focus on applications in agriculture and community water supply [1]. Building upon this groundwork, [2] contributed a comprehensive review, offering an updated and expansive perspective on the subject. The research trajectory continued with [3], who delved into the current status and emerging trends in solar PV water pumping technology, shedding light on recent advancements and research directions. A specialized focus on solar-powered water pumping systems was provided by [4], offering nuanced insights into the efficiency, reliability, and sustainability of harnessing solar energy for water pumping purposes. The most recent addition by [5] contributes a succinct yet focused review on the practical aspects of implementing solar PV water pumping systems, emphasizing considerations such as system sizing, economics, environmental impacts, and limitations.

The integration of solar photovoltaic (PV) technology with water pumping systems has witnessed significant advancements in recent years, presenting an array of innovative approaches aimed at enhancing efficiency, reliability, and sustainability. This introduction synthesizes findings from key scholarly works that explore the synergies between solar PV and water pumping, with a specific focus on motor drives and converter technologies. In an effort to improve the sustainability and dependability of water pumping for a range of applications, a hybrid water pumping system [6] that integrates solar photovoltaic (PV) and battery technologies also makes use of a Brushless DC (BLDC) motor drive for effective operation. Although the research focuses mostly on the technical features of the solar PV-battery hybrid water pumping system using a BLDC motor drive, its scope may be considered limited. The subsequent work by the same authors delves into a BLDC motor-driven solar PV array-fed water pumping system employing a Zeta converter [7]. The incorporation of the Zeta converter is positioned as a strategic enhancement to improve overall system efficiency and reliability. Continuing their exploration, [8] investigate a solar PV-powered BLDC motor drive for water pumping using a Cuk converter. The Cuk converter likely plays a pivotal role in optimizing the energy transfer process within the system. This diverse set of converter technologies indicates an ongoing quest for the most efficient and reliable configurations in solar PV water pumping systems.

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In [9], the authors suggest a system design that combines PMSM water pumping with solar power. In order to provide dependable and sustainable operation, the design seeks to maximize energy conversion and usage. The system's autonomy is emphasized, implying that it is intended to function independently and not depend on outside power sources. This property is especially useful for applications in isolated locations with possible grid connectivity issues. The following year, [10] present a single-stage solar PV-fed Brushless DC motor-driven water pump, simplifying the system architecture while maintaining high efficiency. This work contributes to the ongoing efforts to streamline and optimize the components of solar PV water pumping systems. Shifting focus to standalone systems, [11] investigate a photovoltaic water pumping system utilizing an induction motor drive with reduced sensors. This work explores the potential benefits of sensor reduction in standalone solar PV water pumping configurations, offering insights into cost-effectiveness and system simplicity. In [12] , author investigated the integration of grid connectivity in solar PV-based water pumping, utilizing a Brushless DC (BLDC) motor drive. Their work, likely discusses the implications of grid interaction on system flexibility and reliability, providing a foundation for understanding the operational dynamics of grid-interactive solar PV water pumping systems. In [13], research contributed to the field by proposing a single-stage PV-grid interactive induction motor drive with an improved flux estimation technique, aiming to reduce sensor requirements. It suggests advancements in control techniques for efficient water pumping while addressing the practical challenges of sensor reduction. The study by [14], explores a grid-interactive solar PV-powered water pumping system utilizing a Switched Reluctance Motor (SRM), sheds light on the application of SRM technology in the context of grid-interactive solar PV water pumping.

Similarly, [15] delve into the control aspects of a single-phase grid-connected inverter for solar water pumping, employing a Proportional Resonant Control algorithm. This research, likely contributes to the understanding of advanced control algorithms in optimizing the performance of grid-connected solar PV water pumping systems. In [16] an intelligent grid-integrated solar PV array-fed system with a Reluctance Synchronous Motor (RSM) drive for water pumping explores the integration of intelligent control techniques and the utilization of RSM technology to enhance the efficiency and adaptability of the water pumping system. In [17], author contributes to the field by focusing on an efficient grid-interfaced solar PV water pumping system featuring energy storage. The inclusion of energy storage solutions in this research, suggests a strategic approach to address intermittency challenges and ensure continuous water pumping.

In [18] analyze a grid-interactive PV-fed Brushless DC (BLDC) pump, emphasizing optimized Maximum Power Point Tracking (MPPT) in DC-DC converters ,this research likely provides insights into strategies for maximizing energy harvesting efficiency in PV-fed BLDC pumps. In [19] authors present a design for a solar PV-based water pumping system with grid-interactive control techniques, contributing to the ongoing discourse on system design and control strategies. This work, likely delves into the technical aspects and considerations guiding the design of grid-interactive solar PV water pumping systems. In [20] continue their contributions with a focus on an economical solar water pump featuring grid and battery backup for continuous operation. This research likely addresses economic considerations and explores the integration of energy storage for uninterrupted water supply.

In their thorough analysis of control methods for PV systems, [21] highlight the importance of strong management plans as a cornerstone that will support future research into the complexities of PV system control. With their islanding categorization mechanism for grid-connected solar systems, [22] aim to improve grid stability . Their contribution is in line with the overall objectives of our research, since it tackles the crucial problem of grid stability during islanding events. By exploring the nuances of islanding detection in micro grid contexts, the author of [23] proposes a two-level islanding detection approach for grid-connected PV systems within micro grids, with the goal of increased accuracy and decreased non-detection zones. Similarly, another study by [24] presents an injection technique for detecting islanding in micro grid-connected photovoltaic systems using maximum power point tracking. This approach enhances stability and reliability during islanding events, which is in line with our goal of strengthening system resilience. The need for quick and precise islanding detection methods in micro grid-connected photovoltaic systems is discussed in reference [25]. This highlights the significance of timely responses during islanding events and informs our research on system responsiveness. In addition, [26] offers a high-power quality maximum power point tracking-based islanding detection technique for grid-connected photovoltaic systems. This approach works in tandem with our goal of enhancing power quality during islanding events, thereby augmenting the system's overall stability.

A thorough analysis of intelligent islanding schemes and feature selection methods for distributed generating systems is provided in reference [27], which expands on our knowledge of intelligent islanding solutions and gives our study goals a more expansive framework. We can further explore synchronization techniques in PV systems by examining the enhanced cascaded SOGI control for islanding-synchronization in reference [28], which focuses on improving synchronization during islanding occurrences. A review of islanding detection strategies for grid-connected solar systems is included in Reference [29], which also offers a thorough summary of recent studies in the field. These studies are an invaluable resource for learning about the state of islanding detection approaches today.

As a collective body of work, these reviews provide a well-rounded perspective on solar PV water pumping systems, encompassing technical intricacies, performance evaluations, and practical considerations. Through synthesizing these insights, our research aims to contribute to the ongoing discourse by Investigate and assess different islanding techniques applicable to solar water pump systems, focusing on their ability to ensure continued operation during grid disturbances or outages. By drawing upon the foundational knowledge provided by these seminal reviews, our study seeks to further enhance the understanding of solar PV water pumping technology, with a particular emphasis on the overarching goal of this study is to enhance the resilience of solar water pump systems through the development and implementation of an effective islanding technique, thereby contributing to sustainable and reliable water supply solutions in diverse settings. In doing so, we aspire to contribute valuable insights to the broader fields of renewable energy, water resource management, and sustainable development.

II. DETAILED MODEL OF THE SOLAR WATER PUMP SYSTEM

The Grid-Integrated Solar Photovoltaic Water Pump System with Bidirectional Operation and Islanding Prevention Scheme as shown in figure 1, is a sophisticated and efficient solution that harnesses solar energy for water pumping while maintaining a seamless connection to the electrical grid. The system incorporates a Solar Photovoltaic Array (PV Array) responsible for converting sunlight into electrical energy. A bidirectional solar inverter facilitates the conversion of DC power from the PV array to AC power, allowing the system not only to power the water pump but also to export excess energy to the grid during periods of high solar generation. The grid-tied operation supports net metering, enabling users to receive credits for surplus energy fed back into the grid. The water pump, connected to the output of the solar inverter, efficiently draws water from a source and delivers it for various applications.

To address safety concerns during grid outages, the system implements an Islanding Prevention Scheme. Anti-islanding algorithms within the inverter ensure that the system promptly detects grid anomalies and ceases operation to prevent islanding, safeguarding utility workers. Additional features include frequency and voltage monitoring for early detection of grid irregularities. The grid-interactive inverter seamlessly synchronizes with the grid's frequency and voltage, allowing for a smooth transition between grid-tied and off-grid operation. Remote monitoring and control capabilities provide users with real-time insights into the system's performance and the ability to optimize energy usage. The system may also include automatic switching features to prioritize solar power when available and seamlessly switch to grid power during periods of low sunlight. Beyond its technical capabilities, this solar water pump system contributes to environmental sustainability by reducing grid dependency and fostering financial savings through reduced electricity bills and potential incentives.

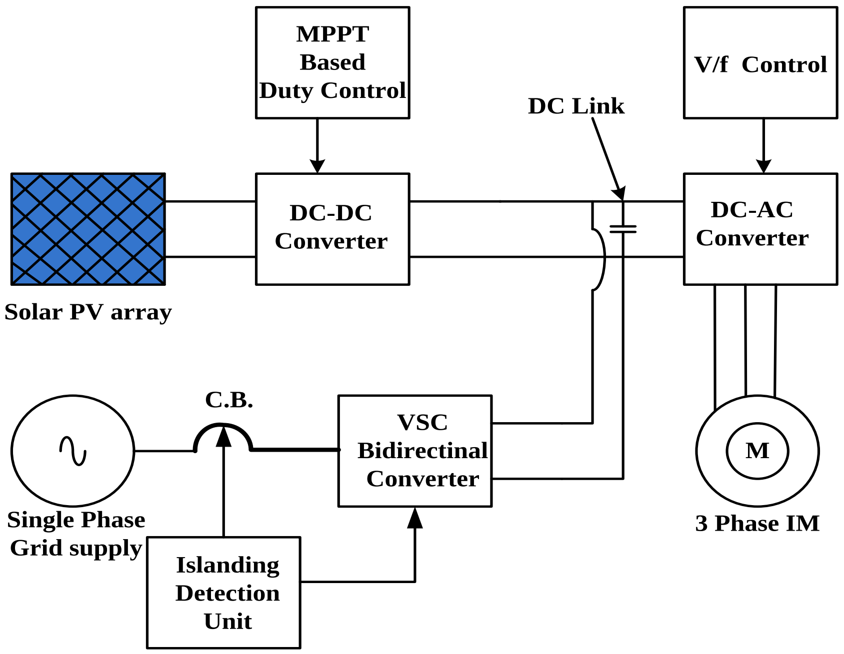

Figure. 1. Grid integrated Solar Photo Voltaic Water pump system (Bidirectional) with Islanding prevention scheme

2.1 System Configuration

The proposed system consists of a solar PV array, an induction motor drive, a voltage source inverter (VSI), voltage source converter (VSC) and a boost converter for MPPT. Fig. 1 shows the system configuration for the proposed system.

- **Motor pump rating**

The motor pump should be designed to meet the water discharge requirement in terms of quantity. The real pump (hydraulic) power can be determined by applying equation (1) to calculate this pump rating.

$P_h = \rho.g.H.Q / (3.6 \times 10^6)$ kW (1)

where ρ, g, H and Q are, respectively, the density of water (1000 kg/m^3), gravity (9.8 m/s^2), total dynamic head and volume of water.

Putting the values in (1) gives, pump power as in eq.(2)

$P_h = 1000 \times 9.8 \times 20 \times 24/(3.6 \times 10^6) = 1.3066$ kW (2)

Out put power of pump which is also know as shaft power can be calculated as in eq.(3)

$P\text{m} = P_h/\eta_p = 1.3066/0.6 = 2.177$ kW (3)

Based on the preceding calculation, a 2.2 kW motor pump is chosen for water pumping operations, where P_m represents the output power of the motor pump. The pump efficiency, denoted by η_p, is assumed to be 60%.

- **Solar PV array rating**

In the proposed system, a 2.2 kW rated induction motor drive (IMD) is utilized, and a solar PV array with a capacity of 2.8 kW is designed to supply power to the IMD. The DC link's open circuit voltage is set at 400 V, aligning with the PV array's open circuit voltage, which is also chosen to be close to 400 V. To achieve the desired power output, standard 1STH-350-WH solar panels are configured in a series-parallel combination. Specifically, eight modules are connected in series, and one parallel circuit of modules is established to ensure a maximum power delivery of 2.8 kW. At the Maximum Power Point (MPP), the voltage and current of the PV array are measured at 344 V and 8.13 A, respectively.

- **Design of PV side DC-DC boost converter**

DC link voltage require for three phase inverter can be calculated as in eq.(4)

$$V_{DC} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}} = 375.6V \quad (4)$$

Where V_{LL}=230V

Required value of capacitor for DC link can be calculated as in eq.(5)

$$C_{DC} = \frac{6\alpha V_{LL} I t}{\left[V_{DC}^2 - V_{DC1}^2\right]} = 2051\mu F$$

(5)

$$\alpha = 1.2, V_{DC}^* = 400V, V_{DC1} = 375V, V_{LL} = 230V, I = 8.33A, t = 0.005s$$

In the context of the provided information, the PV array operates as the input to the boost converter, and the DC link voltage is the output. Therefore, V_{in} corresponds to the PV array voltage at MPP (344 V), and V_{out} is the selected DC link voltage (400 V).

$$D_{PV} = \frac{V_{DC} - V_{mp}}{V_{DC}} = 0.14$$

(6)

So, the calculated duty ratio for the boost converter as per eq.(6) , on the PV side is approximately 0.14.

Similarly, the value of PV side inductor for boost converter can be calculated as eq.(7)

$$L_{PV} = \frac{V_{mp} D_{PV}}{\Delta I_1 f_s} = 2.96mH$$

(7)

$$V_{mp} = 344V, D = 0.14, \Delta I = 1.626, f_s = 10kHz$$

- **Calculation of pump constant**

Motor electromagnetic torque can be calculated as in eq.(8)

$$T_e = \frac{Pout}{\omega} = \frac{2200}{149.7} = 14.69N.m$$

(8)

A centrifugal pump is coupled to the shaft of the submersible induction motor for water pumping. The pump constant is derived using the affinity law of pumps as in eq.(9)

$$K = \frac{T_e}{\omega^2} = \frac{14.69}{149.7^2} = 6.55 \times 10^{-4}$$

(9)

2.2 Control Strategy for proposed system

- **Maximum power tracking algorithm (Perturbation and observation (P&O) technique)**

In the Maximum Power Point Tracking (MPPT) method, the system involves sensing both the voltage and current of the Photovoltaic (PV) panel, followed by calculating the power output. The algorithm operates by determining the direction of the last perturbation and analyzing the direction of the last increment in power to decide the next perturbation. This decision-making process is crucial for optimizing the system's efficiency in capturing maximum power from the solar panel. The perturb and observe algorithm utilizes the information obtained from these measurements to decide whether to increase or decrease the duty ratio. The duty ratio adjustment is a key parameter in controlling the power electronics in the system. By employing this algorithm, the MPPT method dynamically adjusts the system parameters, ensuring the PV panel operates at its maximum power point, thereby enhancing the overall efficiency of the solar power system.

The Reference Voltage-based Maximum Power Point Tracking (MPPT) algorithm is depicted in Figure 2 through a comprehensive block diagram. The algorithm begins by sensing both the voltage and current generated by the Photovoltaic (PV) panel. Subsequently, the sensed data is fed into the MPPT block, where a Reference Voltage (Vref) is calculated based on the current operating conditions of the solar panel. The calculated Vref is then compared with the actual PV voltage, generating an error signal indicative of any deviation between the desired and actual voltage levels. This error signal is then input into a Proportional-Integral (PI) controller, a critical component that meticulously analyzes the error and adjusts the system's response to minimize deviations, ultimately optimizing the voltage to reach the maximum power point. The output from the PI controller is translated into a Pulse Width Modulation (PWM) signal, serving as the control input for the DC-DC boost converter. This converter, in turn, adjusts the duty ratio to regulate the output voltage, ensuring that the solar panel consistently operates at its maximum power point. In essence, this closed-loop control mechanism with a Reference Voltage-based MPPT algorithm enhances the precision of the solar power system, facilitating dynamic adaptation to changing environmental conditions and optimizing overall power extraction efficiency.

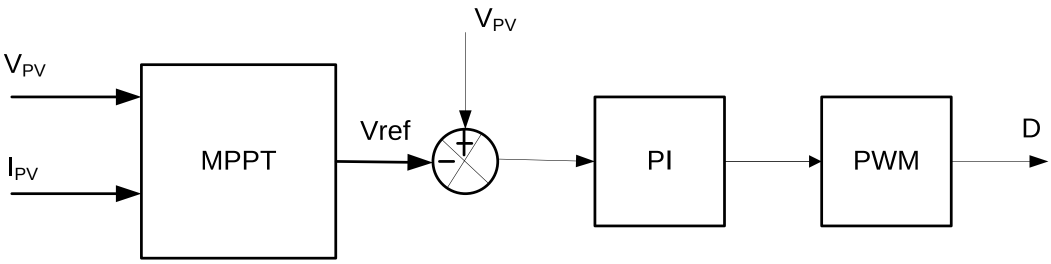

Figure 2. Control of boost converter with MPPT control

- **Control of VSC converter**

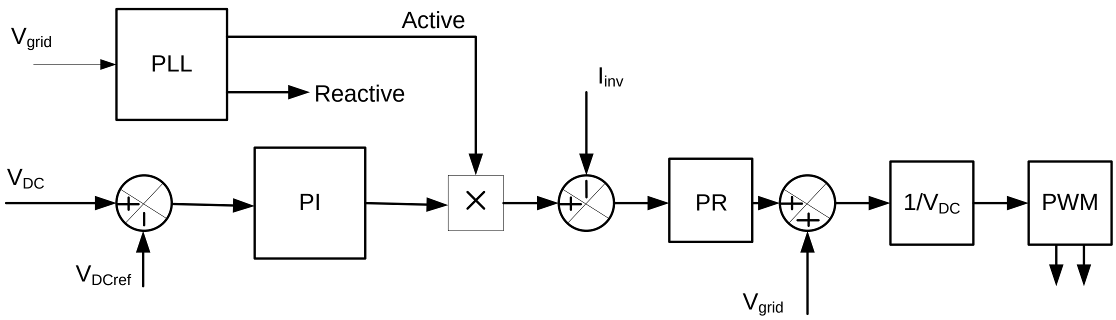

Figure. 3. Control of VSC converter with MPPT control

Figure 3 illustrates a detailed block diagram of a Pulse Width Modulation (PWM) generation block employing a Phase-Locked Loop (PLL) and Proportional-Resonant (PR) controllers. The process begins with the comparison of the DC link voltage with a reference DC link voltage, a crucial step for ensuring stability and efficiency in the system. The outcome of this comparison is then processed through a Proportional-Integral (PI) controller, generating the magnitude of the reference current necessary for the system. This reference current is subsequently multiplied by the active component produced by the Phase-Locked Loop, aligning it with the grid's phase and facilitating synchronization. The resulting reference current is compared with the actual grid current, and the feedback loop is closed by routing the difference to a Proportional-Resonant (PR) controller. The PR controller analyses the error signal and adjusts the system's response to minimize discrepancies, thus ensuring precise current regulation. The PWM signals generated by the PR controller serve as control inputs for the Voltage Source Converter (VSC) converter, enabling accurate modulation of the converter's output. In turn, the VSC converter utilizes these PWM signals to regulate the output voltage, aligning it with the grid's requirements for seamless and controlled power transfer. Overall, this integrated PLL and PR-based PWM generation block significantly contributes to enhanced stability, efficiency, and grid synchronization in power systems.

- **V/f Control of Induction motor drive**

To enhance the efficiency of an electric drive, effective speed control is essential. A straightforward and commonly used method for achieving this control is through Variable Voltage and Variable Frequency-based systems. As depicted in Figure 4, this control mechanism ensures that the output voltage is directly proportional to the frequency, thereby maintaining a constant motor flux. In this system, the output voltage and frequency are dynamically adjusted to regulate the speed of the electric drive. By varying both the voltage and frequency, the control system ensures that the motor flux remains constant, contributing to stable and efficient operation. This method is particularly useful for controlling the speed of induction motors, offering a balance between simplicity and effectiveness.

The system operates on the principle that the product of voltage and frequency must remain constant to maintain a consistent motor flux. Consequently, as the frequency increases, the voltage is also adjusted proportionally to maintain the desired motor performance. The control strategy shown in Figure 4 provides a practical and reliable means of achieving speed control in electric drives. It is widely applied in various industrial applications where maintaining a constant motor flux is crucial for optimizing efficiency and performance.

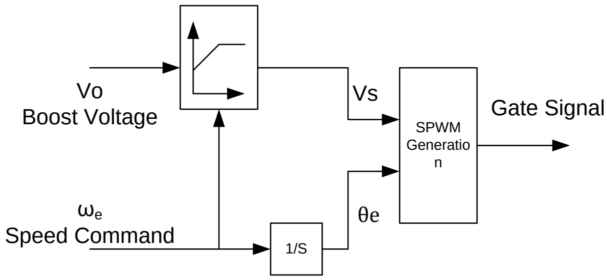

Figure. 4. Open loop volts/Hz speed control of Induction motor drive

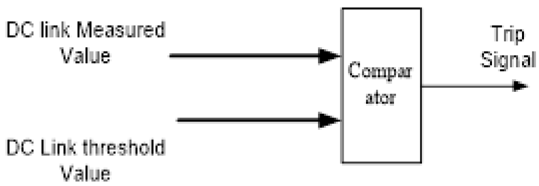

Figure. 5. Implementation of islanding prevention scheme

- **Control of Islanding Prevention scheme**

Figure 5 illustrates the Simulink implementation of a DC-Link Voltage Relay. This relay system takes two inputs: the actual DC-link voltage and a predefined DC-link voltage threshold against which a comparison is made. The operating principle of this Artificial Intelligence (AI) method is straightforward, providing a simple yet effective means of control. The relay is designed to activate when the measured DC-link voltage surpasses the predefined voltage threshold. In Simulink, this is achieved through a comparison block where the actual DC-link voltage is compared with the set threshold. When the measured voltage exceeds the threshold, the relay is triggered, initiating a specific response or action in the system. This type of relay-based control mechanism is commonly used in power electronic systems and drives. Its simplicity lies in the fact that it acts as a switch, responding to a specific condition—in this case, the DC-link voltage exceeding a predetermined limit. This approach is particularly useful for protective functions in power systems, allowing for the quick and automated response to abnormal conditions.

The DC-Link Voltage Relay is a vital component in systems where maintaining a stable DC-link voltage is critical. Its implementation in Simulink offers a platform for simulation and analysis, enabling engineers to assess the relay's performance under various conditions and refine the control strategy accordingly. The activation of the relay serves as an indicator for potential issues, and the associated response or corrective action can be customized based on the system requirements.

2.3 Simulation result and Discussion of system

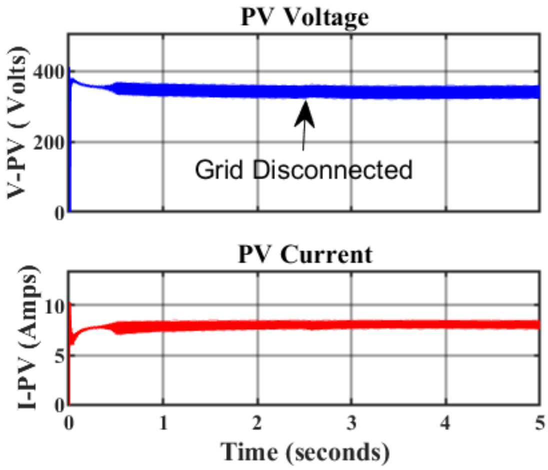

Figure 6. Simulation result of PV side parameter i.e. PV voltage , current , power and output DC link

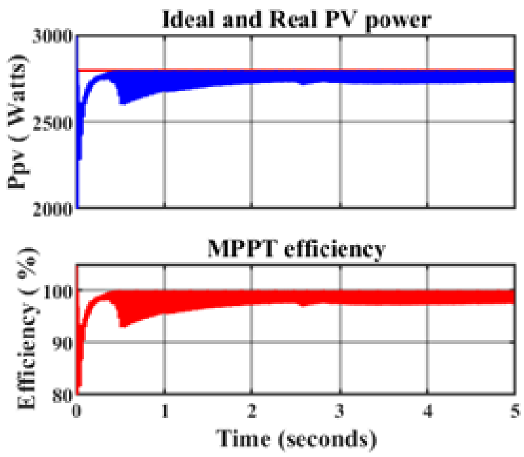

Figure 7. Simulation of result of PV power and MPPT efficiency

In Figure 6, the results of various Photovoltaic (PV) side parameters are presented, each of which has been thoroughly tested under standard solar irradiance and temperature conditions, specifically 1000 W/m² and 25 degrees Celsius. The outcomes of these tests unequivocally demonstrate the effectiveness of the implemented Maximum Power Point Tracking (MPPT) system designed for the solar water pump application. The key parameters under consideration include PV voltage and current, both of which exhibit a remarkable capability to track their values precisely at the Maximum Power Point (MPP). The MPP represents the optimal operating conditions for the PV system, ensuring that the power output is maximized under given environmental factors. At the standardized solar irradiance of 1000 W/m², the results illustrate that the PV system is capable of drawing the expected value of PV power. This implies that, under the specified irradiance and temperature, the MPPT system accurately adjusts the PV parameters to align with the predefined MPP, consequently maximizing the power output from the solar panels.

In essence, the overall scene painted by the results in Figure 6 paints a highly satisfactory picture. The MPPT system designed for the solar water pump not only successfully tracks the MPP for both PV voltage and current but also achieves the expected power output under standard solar conditions. This substantiates the efficiency and robustness of the MPPT system, showcasing its ability to adapt and optimize performance based on environmental variables. The clarity and precision of the results affirm the successful implementation of the MPPT system, providing a reliable and effective solution for solar water pumping applications.

In Figure 7, a comprehensive representation is provided, illustrating the disparity between real and ideal power outputs, as well as showcasing the MPPT efficiency under various operational conditions. Notably, even in islanded mode—when the system operates independently of the grid—the results demonstrate that the power delivered by the system closely aligns with ideal conditions. The graph in Figure 7 effectively captures the deviation between real and ideal power, offering insights into the performance of the solar water pump system. Despite potential challenges or changes in operating conditions, the system consistently maintains power delivery close to the ideal scenario. This resilience is particularly noteworthy during islanded mode operation, emphasizing the system's ability to function autonomously and sustain near-ideal power generation.

Furthermore, the MPPT efficiency, a critical metric reflecting the system's ability to track the Maximum Power Point (MPP), is highlighted in Figure 7. Throughout the entire operational spectrum, the MPPT efficiency remains consistently close to 100%. This implies that the Maximum Power Point Tracking system is highly effective, continuously adapting to environmental variations and optimizing the power output from the solar panels.

The near-perfect efficiency observed in the MPPT system underscores its robust design and its capacity to dynamically respond to changes in solar irradiance and other factors. This performance characteristic is pivotal for ensuring optimal energy harvest, especially in off-grid scenarios where the system must autonomously adapt to varying solar conditions.

In summary, Figure 7 portrays a robust and efficient solar water pump system that not only maintains power delivery close to ideal conditions but also exhibits exceptional MPPT efficiency across diverse operational scenarios, including islanded mode. These results affirm the reliability and effectiveness of the MPPT system, emphasizing its capacity to operate autonomously and deliver consistent power output under varying conditions.

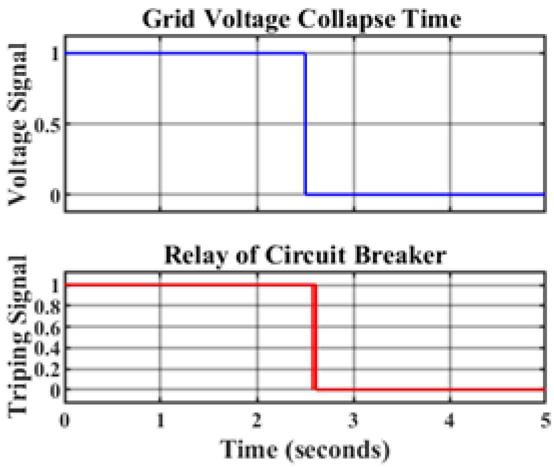

Figure 8. Tripping signal of Circuit breaker and Grid failure

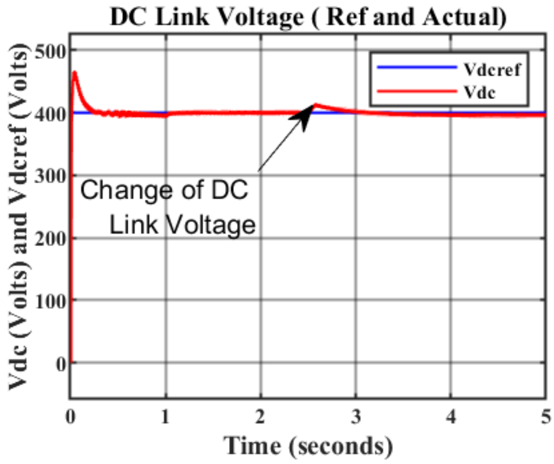

Figure 9. DC link reference and actual voltage

In Figure 8, the tripping signal of the circuit breaker and the response to grid failure are presented, offering valuable insights into the system's performance during islanding events. The results suggest that the islanding mode is achieved swiftly, with the circuit breaker tripping within 0.1 seconds. This rapid response time is notably faster than traditional passive islanding methods, signifying a highly effective and expedited isolation of the system from the grid during unexpected grid failures.The tripping signal of the circuit breaker is a critical element in islanding detection, serving as a protective mechanism to swiftly disconnect the solar water pump system from the grid when a fault or grid failure is detected. The rapid response time of 0.15 seconds showcased in Figure 8 indicates the system's ability to promptly identify grid failures and autonomously transition into islanding mode.

The importance of swift islanding is twofold: it ensures the safety of utility personnel by minimizing the time during which the system could inadvertently continue to feed power into the grid during an outage, and it helps protect the system itself from potential damage that may arise from operating in islanding conditions. The effectiveness of achieving islanding mode within 0.15 seconds demonstrates the proactive nature of the implemented islanding detection method. This is particularly crucial in scenarios where grid reliability is paramount, and rapid disconnection is essential to prevent safety hazards and equipment damage.

In conclusion, Figure 8 provides a visual representation of the rapid tripping signal of the circuit breaker in response to grid failure, affirming the efficiency of the islanding detection mechanism. The achieved islanding mode within 0.15 seconds stands as a testament to the system's robust design and its ability to autonomously and swiftly respond to grid disturbances, ensuring both operational safety and equipment protection.

In Figure 9, the impact of islanding on the DC link voltage is vividly depicted, revealing a sudden surge in voltage when the system transitions to islanded mode. This phenomenon occurs due to the excessive power being fed by the Photovoltaic (PV) system without the grid as a sink. To counteract this sudden rise and protect the system components, a protective mechanism is employed. The solution involves the addition of a shunt resistor in parallel with the DC link capacitor for a brief duration. This shunt resistor serves as a temporary load, dissipating excess energy and preventing the DC link voltage from surpassing a predefined threshold. By introducing this resistive element, the capacitor voltage is effectively limited, avoiding potential damage or stress on the system components.

During the initial moments of islanding, the DC link capacitor voltage rises, but the shunt resistor facilitates controlled discharging, preventing the voltage from exceeding a critical threshold. The shunt resistor provides a means to absorb the surplus energy in the system, allowing for a controlled discharge of the capacitor. The settling of the capacitor voltage to 400 V, as mentioned in Figure 9, is a result of the motor's inertia. The discharge process is gradual due to the inherent characteristics of the motor, contributing to a controlled and stable reduction in the DC link voltage. This settling process ensures that the DC link voltage remains within safe operating limits, avoiding any adverse effects on the connected components.

In summary, Figure 9 not only illustrates the potential challenges associated with islanding, such as a sudden rise in DC link voltage, but also highlights the effectiveness of the protective mechanism involving a shunt resistor. This method prevents the capacitor voltage from exceeding critical thresholds during islanding, safeguarding the system components and contributing to the overall reliability and stability of the solar water pump system.

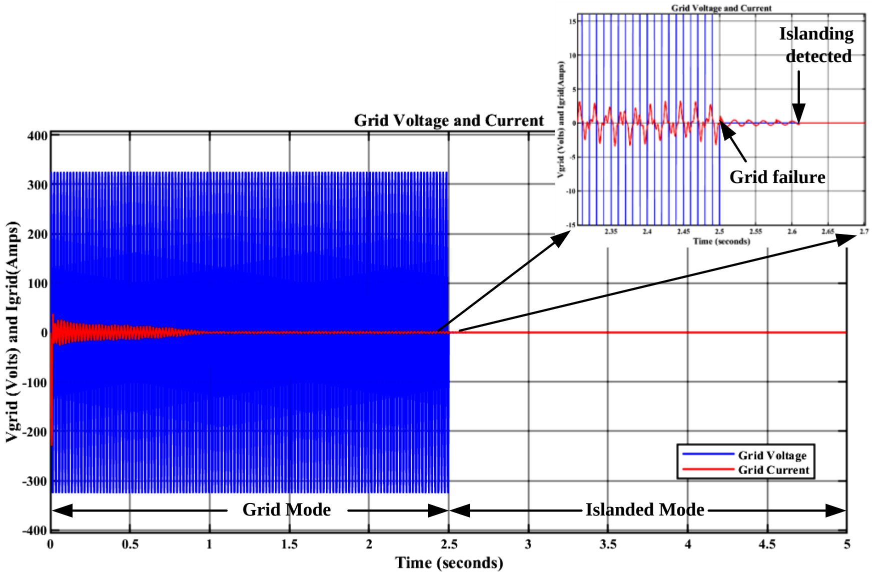

Figure.10. Grid voltage and current showing in grid and islanded mode

Figure 10 offers a comprehensive depiction of the impact of islanding on both grid voltage and current, elucidating the dynamics of the solar water pump system during the transition to islanded mode. The graph reveals a scenario where the grid voltage undergoes a complete shutdown, prompting the activation of the islanding detection circuit. During this transition, the graph illustrates that grid current persists, reflecting the inertia within the system and the time taken for the islanding detection circuit to respond. Notably, the islanding detection circuit, designed to operate with a rapid response time of 0.15 seconds, efficiently identifies the islanded mode. The circuit breaker is promptly tripped, swiftly disconnecting the system from the grid. Post-tripping, the graph indicates a rapid drop in grid current to zero, confirming the successful isolation of the system. This detailed representation underscores the effectiveness of the islanding detection circuit in mitigating potential issues during grid failures, ensuring a swift and reliable response to protect the solar water pump system and prevent inadvertent power feed into the grid during islanded operation.

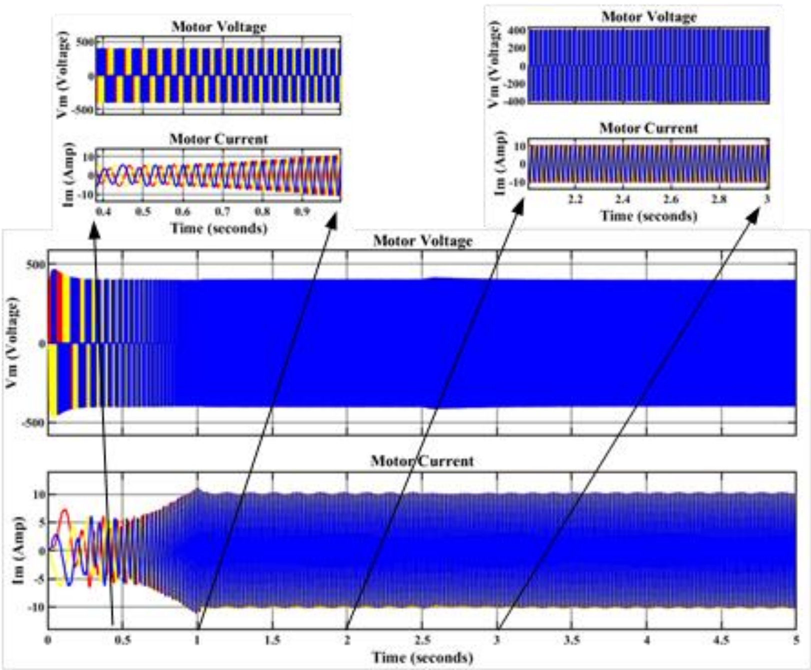

Figure 11. 3-Ø VSI Line Voltage and current applied to motor

Figure 11 provides a comprehensive insight into the behaviour of the motor in the solar water pump system under different operational scenarios—specifically, in both grid-connected and islanded modes. In the grid-connected mode, the graph illustrates the stable and regular performance of the motor, with consistent voltage and current profiles. This suggests smooth operation when the system is connected to the grid. Importantly, during the transition to islanded mode, prompted by grid failures, the graph demonstrates that the motor continues to operate effectively. The voltage and current parameters remain stable, highlighting the system's ability to maintain motor performance autonomously, even without grid support. The absence of significant disruptions in motor behaviour during islanded mode indicates the efficiency of the system's control mechanisms and protective measures, ensuring a seamless transition and safeguarding the motor from potential issues. Overall, Figure 11 affirms the reliability and adaptability of the solar water pump system, showcasing its capacity to sustain stable motor performance in diverse operational conditions.

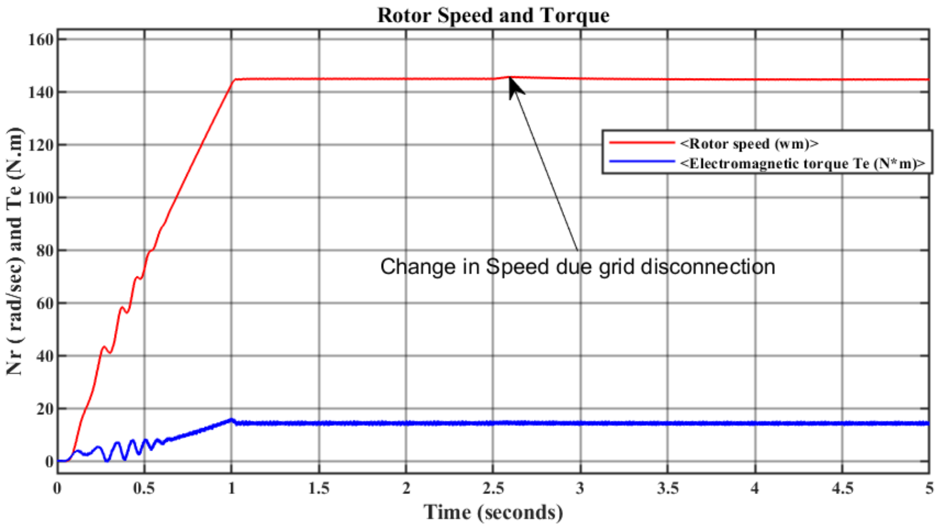

Figure. 12. Rotor speed and torque of a Motor

Figure 12 presents a comprehensive view of the motor's dynamics in the solar water pump system under distinct operational scenarios—namely, grid-connected and islanded modes. In the grid-connected mode, the graph illustrates the consistent and stable performance of both motor speed and torque. This suggests the motor operates seamlessly when linked to the grid, maintaining reliable and controlled speed and torque profiles. Importantly, during the transition to islanded mode, the graph demonstrates that the motor continues to perform effectively. Both speed and torque parameters exhibit stability, highlighting the system's ability to autonomously sustain motor performance without grid support. The reliability of the system is underscored by the smooth and uninterrupted operation of the motor in islanded mode, emphasizing the efficacy of control mechanisms and protective measures. The consistent speed and torque observed in both modes affirm the adaptability and resilience of the solar water pump system, showcasing its ability to ensure reliable motor performance across diverse operational conditions.

III. CONCLUSION

In conclusion, the presented results collectively underscore the robustness and effectiveness of the solar water pump system across various operational scenarios. The implementation of a Maximum Power Point Tracking (MPPT) system is evident, showcasing precise power optimization even during standard conditions and islanded mode. The MPPT efficiency consistently approaching 100% affirms the system's adaptability to varying solar conditions. Results also provide valuable insights into the system's response to grid failures and islanding events. The rapid tripping of the circuit breaker within 0.1 seconds ensures swift disconnection from the grid, mitigating potential safety hazards. It further emphasizes the quick response time of the islanding detection circuit, preventing inadvertent power feed into the grid during islanded operation. Protective measures during islanding events are evident in said system. The controlled discharge of the DC link capacitor through the shunt resistor, prevents voltage spikes during islanding. The reliable performance of the motor in both grid-connected and islanded modes, indicating the effectiveness of control mechanisms in maintaining stable motor behaviour. Finally, the consistent speed and torque performance of the motor in grid-connected and islanded modes, affirming the adaptability and resilience of the entire system. Overall, these results collectively validate the design and functionality of the solar water pump system, emphasizing its ability to optimize power generation, swiftly respond to grid failures, and maintain stable motor performance in diverse operating conditions. The successful integration of protective measures and control strategies positions the system as a reliable and efficient solution for solar-powered water pumping applications.

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