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Grid-Connected Solar Water Pumps with Reduced Converter Topology for Cost-Effective Brilliance

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Abstract: - This study delves into the optimization of grid-connected solar water pumps by introducing a reduced topology, aiming to enhance both efficiency and cost-effectiveness. The research focuses on streamlining the system's configuration, employing innovative techniques to minimize complexity and component requirements. By implementing this reduced topology, the study anticipates substantial cost savings in the overall system while maintaining or even improving its operational brilliance. Through a comprehensive analysis of the proposed approach, this research offers valuable insights into the potential for significant advancements in grid-connected solar water pump technology, paving the way for sustainable and economically viable water pumping solutions.

Keywords: Grid-connected, Solar water pumps, Reduced Topology, Cost-effectiveness, Efficiency optimization

I. INTRODUCTION

The global demand for sustainable and energy-efficient water pumping solutions, particularly in rural and isolated zones, has led to significant research in the field of grid-connected solar water pumping systems. This literature review synthesizes the findings from various studies to present a comprehensive understanding of the progress made in this domain. The early works by Slabbert and Malengret [1] and Ramos et al. [2] lay the foundation for grid-connected solar water pumping. These studies emphasize the importance of solar-powered pumps in supplying water to remote areas, with a focus on case studies and practical applications. Khan et al. [3] provide insights into the design and performance analysis of water pumping using solar photovoltaic (PV) systems. Rawat et al. [4] extend this by reviewing modeling, design methodology, and size optimization of photovoltaic-based water pumping, considering both standalone and grid-connected systems. Several studies focus on the integration of solar water pumping systems with the grid. Kumar and Singh [5, 6] explore grid-interfaced solar PV systems utilizing brushless DC motor drives, emphasizing the importance of bidirectional power flow and intelligent control strategies [7]. Singh and Murshid [8] introduce a grid-interactive permanent-magnet synchronous motor-driven solar water pumping system, showcasing advancements in motor technologies. Mishra and Singh [9, 10] propose improved control techniques for single-stage solar-powered water pumping systems, highlighting advancements in efficiency and power flow management. Parmar et al. [11] propose a novel back-to-back inverter configuration for solar water pumping and grid-tie applications.

The study focuses on enhancing the overall efficiency and performance of solar water pumping systems. Murshid and Singh [12] investigate power quality improvement in grid-integrated solar water pumping systems using Vienna converters. Kumar and Singh [13] investigate grid-interactive solar PV-based water pumping using a brushless DC motor drive. The study emphasizes the importance of efficient and controlled power delivery in such systems. Murshid and Singh [14] address power quality improvement in grid-integrated solar water pumping systems using a Vienna converter. The research focuses on enhancing the reliability and stability of the system. Rahman et al. [15] present a cascaded multilevel qZSI-powered single-phase induction motor for isolated grid water pump applications, emphasizing enhanced control algorithms. Mantri et al. [16] conduct a comparative study on grid-connected vs. off-grid solar water pumping systems for agriculture in India, providing insights into the techno-economic aspects of these systems. Recent works by Mishra et al. [17, 25] introduce emerging

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technologies such as switched reluctance motors and energy storage, contributing to the efficiency and reliability of grid-connected solar water pumping systems.

Mishra and Singh [18] present a grid-integrated solar-powered water pump with power flow management. The study contributes to optimizing power flow, ensuring efficient operation, and minimizing losses in the system. Yalavarthi and Singh [19] introduce a grid-integrated solar PV array-fed water pumping system using a switched reluctance motor drive. The research highlights the application of advanced motor technologies in solar water pumping. Aliyu et al. [20] provide a comprehensive review of solar-powered water pumping systems, summarizing various components, configurations, characteristics, and performance metrics.

The study offers insights into the diverse aspects of these systems. Lilhare et al. [21] present a grid-supported solar water pump system, focusing on its efficiency and reliability. The study addresses the practical implementation of solar water pumping with grid support. Sharma et al. [22] introduce a grid-connected solar PV-fed constant power water pumping system. The research emphasizes the constant power delivery aspect, contributing to stable and reliable water pumping. V and P [23] discuss the control of a single-phase grid-connected inverter using a proportional resonant control algorithm for solar water pumping systems. The study focuses on enhancing control strategies for improved system performance. Verma et al. [24] provide a comprehensive review of solar PV-powered water pumping systems, summarizing recent developments and technologies.

The study contributes to understanding the state-of-the-art in solar water pumping. In recent years, solar photovoltaic (PV) technology has gained prominence in water pumping systems, presenting sustainable solutions for remote and off-grid areas. A study by Manideep and Priya explores the augmentation of grid-connected solar PV systems for water pumping, specifically emphasizing the use of an induction motor to enhance overall system performance [26]. Additionally, Mishra et al. contribute an economical solar water pump design with grid and battery backup, ensuring continuous operation by addressing challenges associated with solar intermittency [27]. Furthermore, Kar et al. propose a novel approach in Circuit World, employing colliding body optimization techniques in a grid-connected solar PV-fed brushless DC motor drive for water pumping [28]. These diverse advancements underscore the evolving landscape of solar PV applications in water pumping systems, encompassing efficiency improvements, continuous operation strategies, and innovative optimization techniques.

The preceding discussion highlights the need for improvements in the configuration, complex control structure, and efficiency of the grid-connected solar water pump system. The current research article is dedicated to addressing these challenges and enhancing the system's effectiveness through innovative solutions. This study particularly concentrates on minimizing the number of converters used in grid-connected systems, aiming to reduce the overall system size. This reduction not only contributes to cost savings but also simplifies the control structure. Additionally, the article proposes the integration of a standalone controller, such as v/f control, to address vulnerabilities during grid outages, ensuring continuous water pumping even in the absence of grid power.

II. REDUCED CONVERTER TOPOLOGY FOR SOLAR WATER PUMP SYSTEM

The block diagram as shown in figure 1 , outlines a solar power system comprising a solar PV array, a DC-DC boost converter, a DC-AC inverter (single-phase), a single-phase induction motor, and a single-phase grid connection. The solar PV array captures sunlight and converts it into direct current (DC) electricity. To ensure efficient energy utilization, a DC-DC boost converter regulates and increases the DC voltage from the solar panels. The boosted DC voltage is then fed into a DC-AC inverter, transforming it into single-phase alternating current (AC). This AC power is subsequently utilized to drive a single-phase induction motor, converting the electrical energy into mechanical energy for specific applications. The entire system is interconnected with the single-phase grid, allowing bidirectional energy flow. In instances of insufficient solar energy, the system can draw power from the grid, and surplus energy can be fed back into the grid, contributing to overall energy sustainability. The rating used for the system is calculated as follows

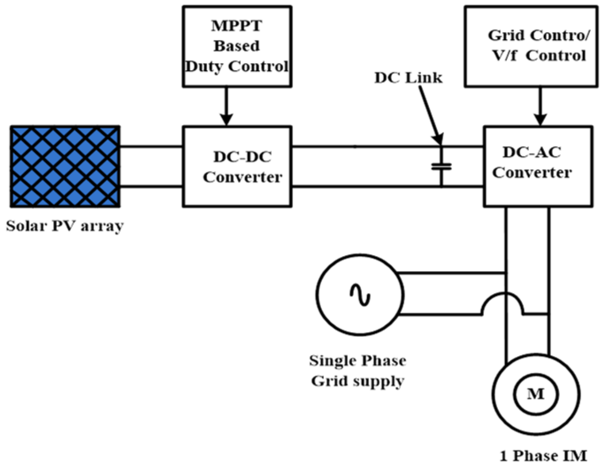


Figure 1 Reduced converter topology for Solar Water Pump System

A. Motor pump rating

The motor pump should be chosen so as to meet the requirement of according to the amount of water discharge. The real pump (hydraulic) power can be computed to get this pump rating as

$$P_h = \rho.g.H.Q \qquad Kw \tag{1}$$

where ρ is the density of water (1000 kg/m^3) , g is gravity (9.8 m/s^2), H is total dynamic head (24 m) and Q refer as volume of water (20 m^3) respectively. Above all value are putting in (1) gives, a pump power as

$$P_h = 1.3066 \qquad Kw$$

Now , shaft power can be calculated as

$$P_m = \frac{P_h}{\eta} = 2.177 \qquad Kw \tag{2}$$

where Pm is the output power of motor and η is the pump efficiency, which is considered as 60%. On the basis of above calculation, a 2.2 kW motor pump is consider for operation of water pumping.

B. Solar PV array rating

For the suggested setup, an induction motor with a 2.2 kW rating is employed. The induction motor drive (IMD) is intended to be fed by a 2.8 kW solar PV array. The DC link's selected open circuit voltage of 400 V is covered in the section that follows. The PV array's open circuit voltage is chosen to be nearer 400 V. To give the system the required electricity, one SolTech 1STH-350-WH solar panel is linked in both series and parallel configurations. A maximum power of 2.8 kW is produced by combining 8 modules in series with 1 parallel circuit of modules. At MPP, the array's voltage and current are 344 V and 8.13 A, respectively.

C. Design of PV side DC-DC boost converter

For given line voltage V_{LL} = 230V, the DC link voltage require for three phase inverter can be calculated as

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}} = 375.6V \tag{3}$$

For given DC link voltage, following parameter is considered,

α = 1.2, Vdc* = 400V, Vdc = 375V, V_{LL} = 230V, I = 8.33A, and t = 0.005 s. So, the value of capacitor require for DC link can be calculated using equation (4)

$$C_{dc} = \frac{6.\alpha.V_{LL}.I.t}{\left(V_{DC}^{*\ 2} - V_{DC}^{\ 2}\right)} = 2051\mu F \tag{4}$$

To operate the PV side boost converter, the required duty ratio can be calculated using equation (5) whereas the value of V_{dc} =400V and V_{mp}=344V taken for calculation.

$$D = \frac{V_{DC} - V_{mp}}{V_{DC}} = 0.14 \tag{5}$$

For smooth operation, inductor element for boost converter can be calculated as (6)

$$L_{pv} = \frac{V_{mp}D}{\Delta I.f_s} = 2.96\,mH \tag{6}$$

D. Calculation of pump constant

Required electromagnetic torque of motor pump can be calculated as

$$T_e = \frac{P_m}{\omega_s} = 14.69\,N.m \tag{7}$$

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 (8)

$$K = \frac{T_e}{\omega^2} = 6.55\times 10^{-4} \tag{8}$$

III. CONTROL SYSTEM FOR REDUCED TOPOLOGY

A. Grid Connected Mode

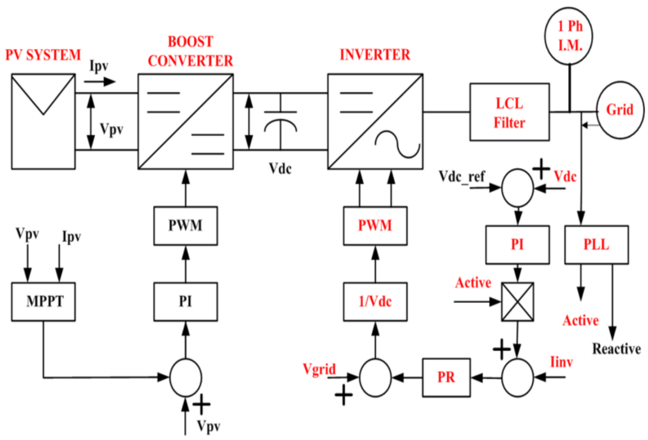


Figure 2 Control block diagram of grid connected mode

In the extended control block diagram of a grid-connected solar system with P&O MPPT and PLL-based grid control as shown in figure 2, the integration of a motor connected to the grid introduces an additional component to the system. The single-phase induction motor, driven by the AC power generated by the inverter, is an essential element for converting electrical energy into mechanical work. The inverter, guided by the PLL-based grid control, ensures that the motor receives synchronized and regulated power from the grid, maintaining a consistent and reliable operation.This interconnected system demonstrates the versatility of grid-connected solar setups, where surplus energy from the solar PV array can be harnessed to drive applications like the single-phase induction motor. The combination of P&O MPPT for efficient solar energy extraction, PLL-based grid control for synchronization, and a connected motor for mechanical work exemplifies a comprehensive and integrated approach towards sustainable energy utilization within a grid-connected environment.

B. Islanded Mode

In an islanded mode solar power system, the control block diagram as shown in figure 3 , integrates the Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm for continuous optimization of the solar PV array's operating point, maximizing power output. Additionally, the system employs open-loop Voltage by Frequency (V/f) control to regulate the inverter's output in the absence of grid synchronization. This V/f control strategy maintains a stable voltage-to-frequency ratio, ensuring reliable power supply to connected loads within the isolated system. Together, the P&O MPPT algorithm and open-loop V/f control facilitate efficient and self-sufficient operation, allowing the solar power system to function independently without a connection to the main utility grid.

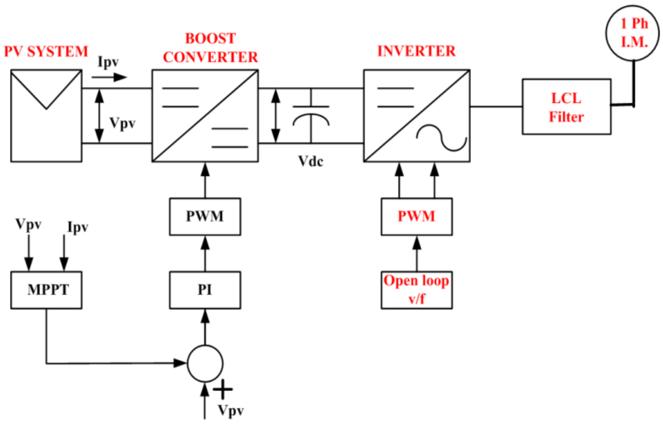


Figure 3 Control block diagram of islanded mode

IV. RESULT AND DISCUSSION

A. Grid Connected Mode

The solar water pump system was tested under standard solar irradiance and temperature conditions while operating in grid-connected mode. In a simulation spanning from 2 seconds to 5 seconds, the system underwent dynamic changes in solar irradiance. Specifically, the solar irradiance level fluctuated from 1000 W/m² to 500 W/m² and then reverted back to 1000 W/m². This simulated scenario allows for the assessment of the system's response and performance under varying solar conditions, helping to evaluate its resilience and efficiency in adapting to dynamic changes in environmental factors.

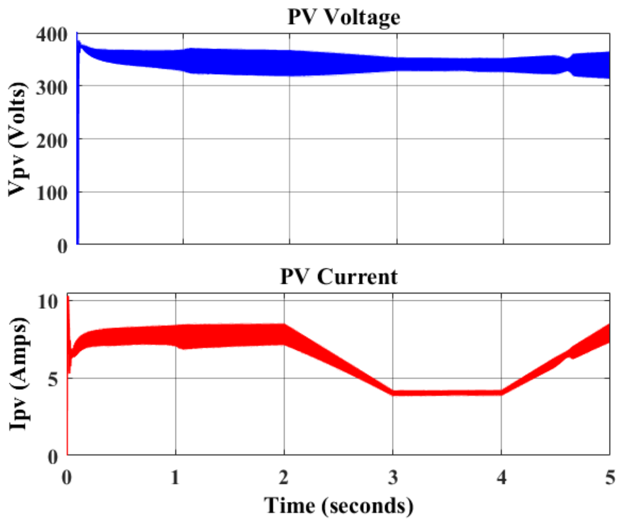


Figure 4 PV voltage and current in grid connected mode

Figure 4 presents results depicting the PV voltage and current profiles during the grid-connected mode. The analysis reveals that the PV voltage consistently operates at its maximum operating point not only at the standard solar irradiance level of 1000 W/m² but also when the irradiance dynamically changes to 500 W/m² and subsequently returns to 1000 W/m². Similarly, the PV current exhibits a corresponding behavior, aligning with its maximum operating point both at 1000 W/m² and 500 W/m². This consistency in reaching and maintaining optimal operating points under varying solar irradiance conditions underscores the effectiveness of the system in grid-connected mode, showcasing its capability to adapt and perform efficiently across different environmental scenarios.

In Figure 5a, the results illustrate the grid voltage and current profiles over a simulation time period from 1.5 to 2.5 seconds. The findings indicate that the voltage and current generated by the Voltage Source Inverter (VSI) exhibit sinusoidal characteristics and are nearly in phase. Additionally, the generated current experiences a reduction corresponding to the decrease in solar power generation, as depicted in Figure 5b. Moving to Figure 5c, the outcomes represent the grid voltage and current during a simulation time span from 3.5 to 4.5 seconds. Similar to the previous scenario, the voltage and current from the VSI maintain sinusoidal waveforms and remain nearly in phase. However, in this case, the generated current increases in tandem with the rise in solar power generation, as illustrated in Figure 5d. Figure 5e displays the results of grid voltage and current dynamics during the simulation time window of 3 to 4 seconds. The findings suggest that the voltage and current generated by the VSI maintain sinusoidal characteristics and are nearly in phase. Interestingly, the generated current remains constant as solar power generation holds steady at 500 W/m², as depicted in Figure 5f. These detailed observations offer valuable insights into the system's performance under varying solar conditions, emphasizing its adaptability and stability in grid-connected mode.

In Figure 6, the presented results highlight the PV power for both ideal and real scenarios. The findings underscore the effectiveness of the control algorithm in consistently tracking the maximum power point of the PV curve. Notably, the conversion of power demonstrates a high level of efficiency, consistently ranging between 90% and 100% throughout the entire simulation period. This suggests that the implemented control strategy is successful in optimizing the operation of the solar power system, ensuring that it consistently operates at its peak performance by efficiently extracting and converting solar energy. The results in Figure 5 validate the robustness of the control algorithm in maintaining optimal power generation efficiency under varying conditions, reinforcing the reliability and effectiveness of the system.

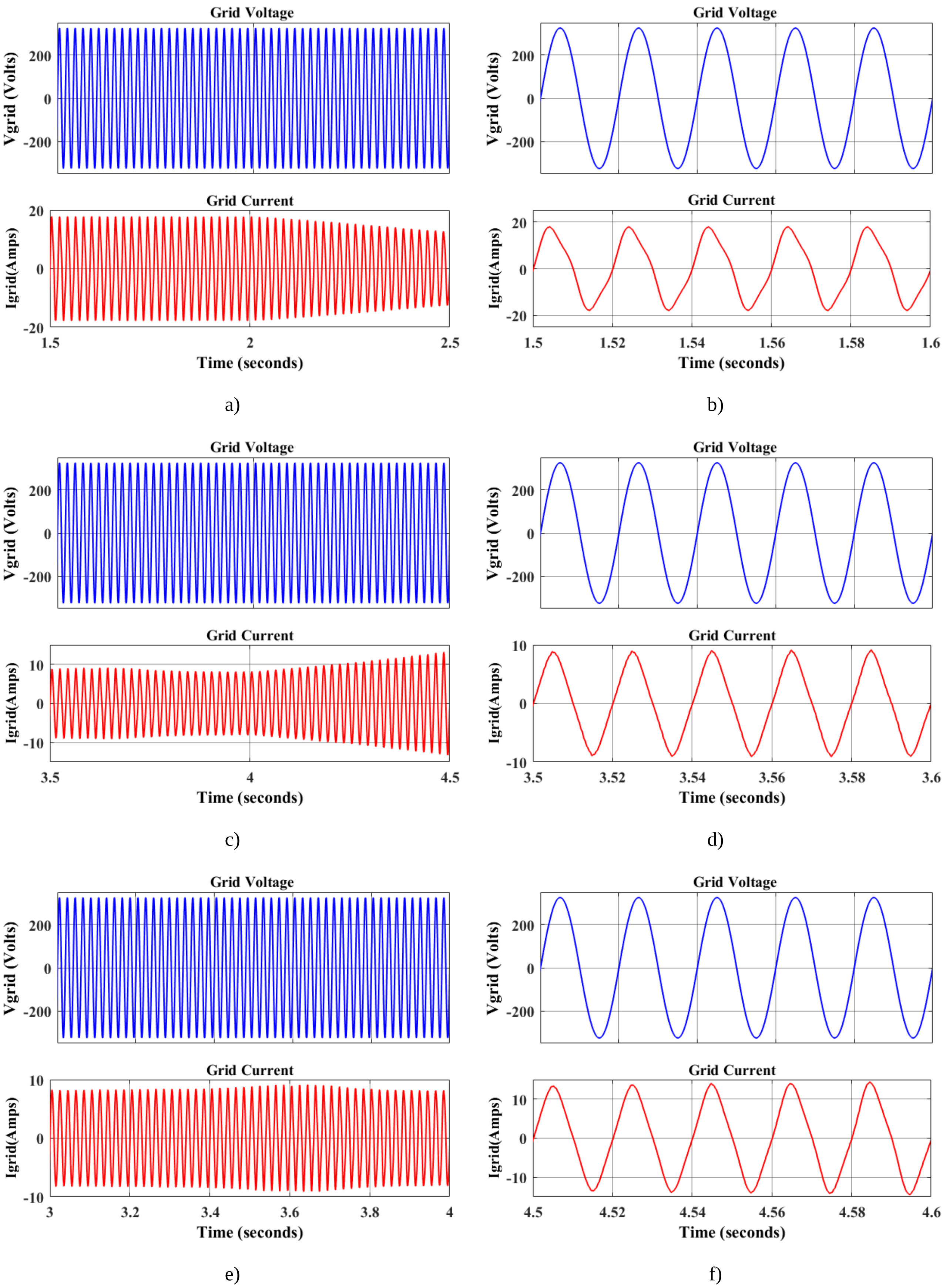


Figure 5 Grid Voltage and Current in grid connected mode

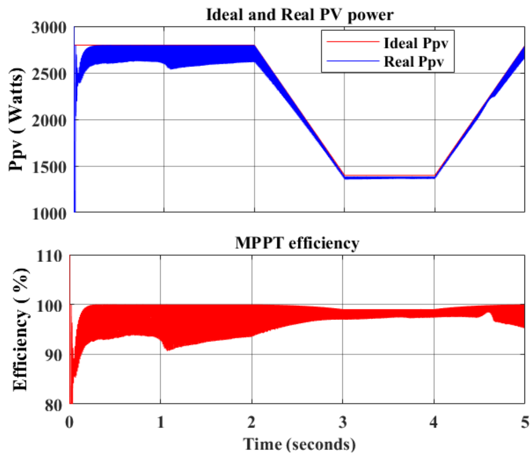


Figure 6 Ideal and real PV power and its efficiency in grid connected mode

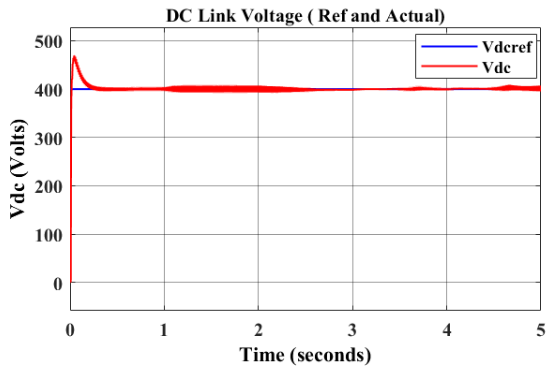


Figure 7 DC link voltage in grid connected mode

In Figure 7, the presented results depict the DC link voltage, revealing a noteworthy alignment between the actual DC voltage and the reference DC link voltage. This congruence signifies the proper functionality of the controller. The close match between the actual and reference values indicates that the control system is adept at regulating and maintaining the DC link voltage at the desired level. This successful control of the DC link voltage is crucial for the overall stability and efficient operation of the solar power system, emphasizing the effectiveness of the implemented control mechanism in ensuring the proper functioning of the system components. The results in Figure 7 provide confidence in the robustness of the controller, affirming its ability to sustain the desired DC link voltage for optimal performance of the solar power system.

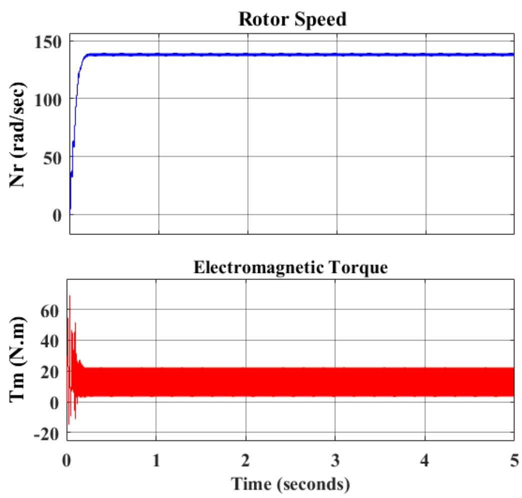


Figure 8 Motor speed and torque in grid connected mode

In Figure 8, the depicted response of motor speed and torque in grid-connected mode reveals significant insights into the system's performance. The results indicate that the motor operates at a speed slightly below its rated speed, showcasing a stable and controlled operation. Despite variations in solar irradiation, the motor consistently maintains a constant speed throughout its operation. This observation suggests that the motor's performance remains unaffected by fluctuations in solar power generation, emphasizing the system's resilience and stability due to its connection to the grid. The ability of the motor to operate at a steady speed, even amid changes in solar conditions, highlights the grid's role in mitigating the impact of such variations, ensuring the motor's consistent and reliable performance in grid-connected mode.

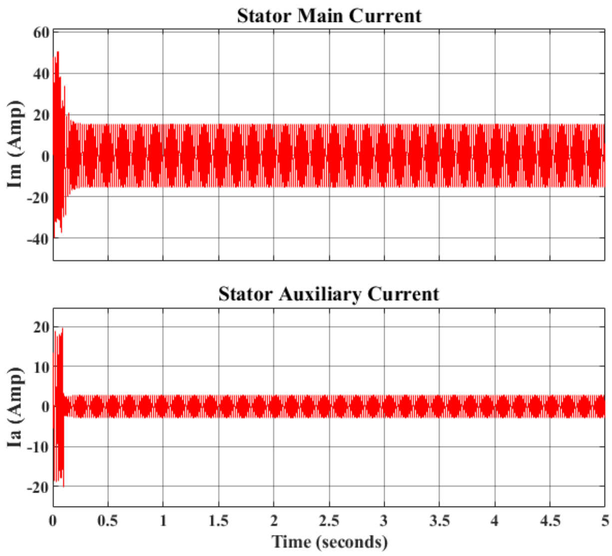


Figure 9 Motor main and auxiliary current in grid connected mode

In Figure 9, the results during grid-connected mode reveal a notable characteristic of the motor operation: a consistent and constant current draw. Despite fluctuations in solar power stemming from changes in solar irradiance, the motor exhibits a behavior wherein its current draw remains unaffected. This steady current draw underscores the system's resilience to variations in solar conditions, with the motor maintaining its operational stability and performance. The observed constant current draw during grid-connected mode suggests that the impact of solar power changes is mitigated, emphasizing the system's ability to ensure a reliable and unwavering motor operation through its connection to the grid. The findings in Figure 9 reinforce the effectiveness of the grid-connected setup in providing stability to the motor's electrical characteristics, contributing to the overall robustness of the solar power system.

B. Islanded Mode

In this operational mode, the solar water pump system operates independently, with the grid isolated from its functionality. The testing methodology mirrors that of the grid-connected mode, ensuring a comprehensive evaluation of the system's performance. Similar to the grid mode tests, the solar water pump system is subjected to standard solar irradiance and temperature conditions during the testing phase. The testing sequence includes a dynamic simulation from 2 seconds to 5 seconds, introducing variations in solar irradiance from 1000 W/m² to 500 W/m² and back to 1000 W/m². The system's response is closely monitored, assessing key parameters such as PV voltage, current, and power, as well as the efficiency of the control algorithm and the behavior of the DC link voltage. The outcomes of these tests aim to gauge the system's adaptability and effectiveness when operating in isolation from the grid, providing valuable insights into its performance under varying solar conditions. This comprehensive testing approach ensures a thorough understanding of the solar water pump system's capabilities and robustness in stand-alone operation.

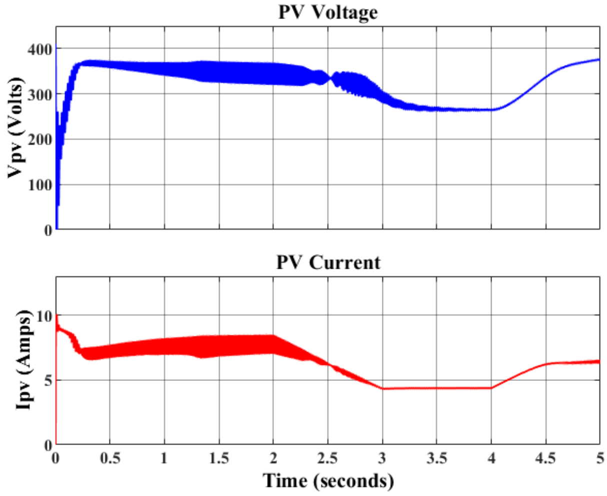


Figure 10 PV voltage and current in islanded mode

In Figure 10, the observed behaviour of the PV voltage and current in islanded mode reveals a noteworthy trend. While the system adeptly tracks its operating point under normal conditions, a slight deviation is evident during dynamic changes in solar irradiation. Although the impact of this deviation may not be substantial, it signals an opportunity for improvement in the controller's design for this operational mode. The results suggest that, despite the system's general effectiveness, there is room for enhancing the robustness of the controller to better handle dynamic variations in solar conditions during islanded operation. This insight implies that further refinements in the control algorithm could contribute to minimizing deviations and ensuring more precise tracking of the desired values. Recognizing this scope for improvement underscores the on-going efforts to enhance the system's performance and efficiency in islanded mode, reinforcing the commitment to optimizing the solar water pump system under diverse operating scenarios.

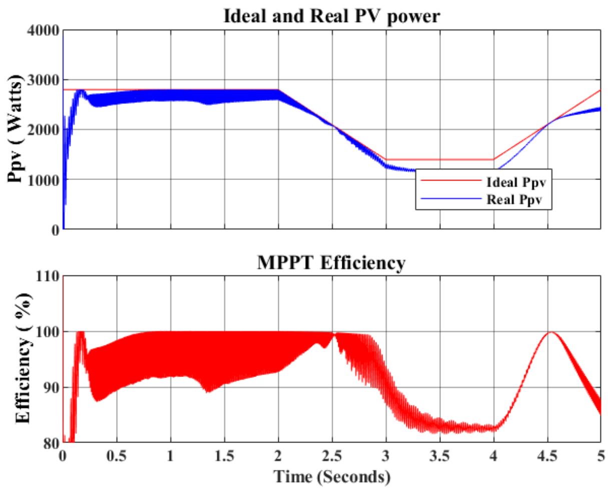


Figure 11 Ideal and real PV power and its efficiency in islanded mode

In Figure 10, where the PV voltage and current behaviour in islanded mode is analysed, the slight deviation observed during dynamic changes in solar irradiation carries implications for both ideal and real power tracking which is shown in figure 11. The tracking of ideal power, which represents the expected power generation under optimal conditions, may exhibit discrepancies during these dynamic shifts. While the system generally follows its operating point, the observed deviation indicates a potential impact on the accuracy of tracking ideal power, suggesting an area for improvement in the controller's design.

Similarly, the tracking of real power, which represents the actual power output considering real-world conditions, might also be affected during these dynamic solar irradiation changes. The deviation in PV voltage and current from the desired values implies that the real power output may experience fluctuations, and the controller could benefit from improvements to enhance the precision of real power tracking.

In Figure 12, the observed behavior of the DC boost converter during dynamic changes in solar irradiation reveals a noteworthy deviation from the reference DC link voltage. Specifically, the DC link voltage fluctuates from 400 V to 280 V. This observation underscores a crucial aspect of standalone mode, indicating a requirement for the design of a new controller to ensure a constant DC link voltage.

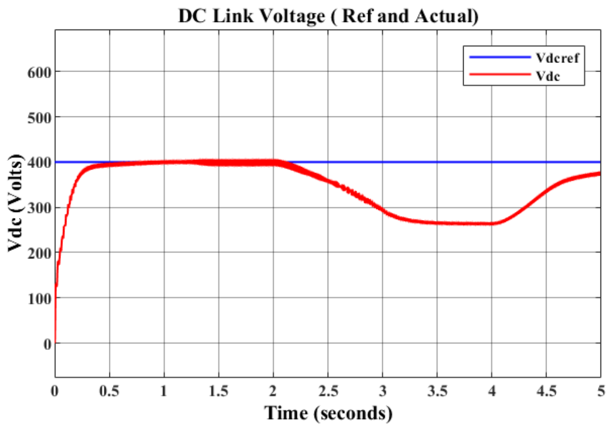


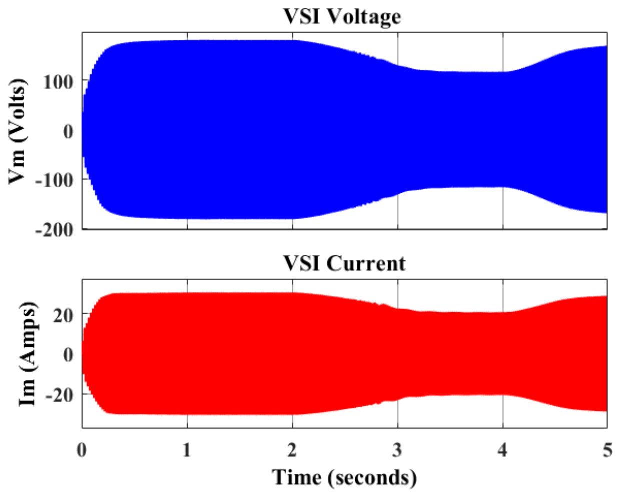
Figure 12 DC link voltage in islanded mode

The deviation in DC link voltage during dynamic solar conditions suggests that the current controller may not be effectively regulating the output voltage under varying irradiance levels. Designing a new and improved controller with enhanced capabilities is essential to maintaining a stable and consistent DC link voltage. This not only contributes to the overall reliability of the system but also ensures that the connected loads receive a steady and well-regulated power supply, even in the absence of the grid.

In Figure 13a, the results for single-phase Voltage Source Inverter (VSI) voltage and currents during islanded mode are illustrated. Subsequently, in Figures 13b, 13c, and 13d, the outputs of the VSI are depicted, showcasing sinusoidal waveforms. These sine wave outputs are achieved through the designed LCL filter connected at the output of the VSI, which plays a crucial role in shaping the voltage and current waveforms. The sinusoidal nature of the VSI outputs not only attests to the effectiveness of the LCL filter design but also demonstrates the system's ability to generate clean and well-filtered power during islanded operation. Additionally, the figures highlight the impact of dynamic variations in solar irradiation on the generated VSI voltage and current. This observation sheds light on how the system responds to changes in solar conditions, providing valuable insights into the system's performance and its ability to adapt to varying environmental factors during standalone operation. The LCL filter's role in smoothing out the generated waveforms contributes to the overall quality and stability of the electrical output in islanded mode.

In Figure 14, the results portraying motor speed and torque dynamics provide valuable insights into the performance of the system. Under normal conditions, the motor operates at a speed slightly below its rated level but remains relatively constant. However, during dynamic changes in solar irradiation, a significant drop in motor speed is observed. This observation suggests that, while the motor speed may vary during fluctuations in solar irradiation, it remains operational and capable of pumping water. The drastic drop in speed indicates the system's adaptability to changing solar conditions, enabling the motor to continue functioning even when confronted with dynamic variations in sunlight intensity. The ability of the motor to withstand and adjust to such changes in solar irradiation underscores the robustness of the system for water pumping applications. Despite variations in solar power, the motor's operational resilience ensures continued functionality, emphasizing the suitability of the solar water pump system for dynamic and unpredictable environmental conditions.

In Figure 15, the depicted results showcase the motor main and auxiliary currents during both static and dynamic changes in solar irradiation. Under static conditions, where solar irradiation remains constant, the motor currents provide a baseline representation of the electrical load on the system. The main and auxiliary currents likely exhibit steady values indicative of the motor's standard operational state. During dynamic changes in solar irradiation, the figure captures how the motor currents respond to fluctuations in solar power generation. The dynamic nature of these changes is reflected in the varying motor currents, illustrating the system's adaptability to different levels of solar irradiation. The auxiliary current, in particular, may play a role in providing supplementary power or control functions, and its response during dynamic changes could reveal insights into the system's efficiency and stability under varying solar conditions.



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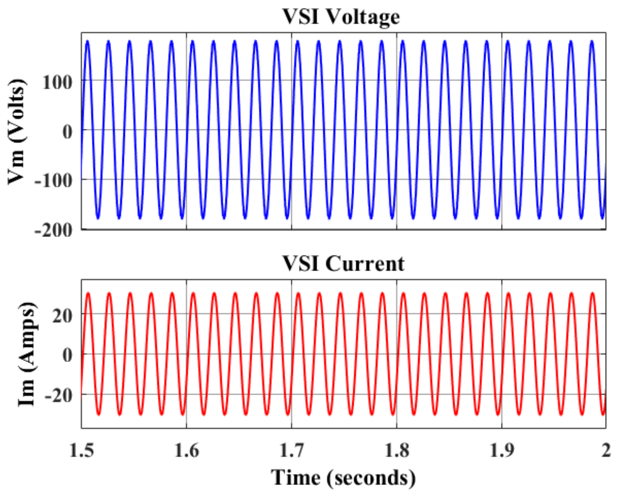

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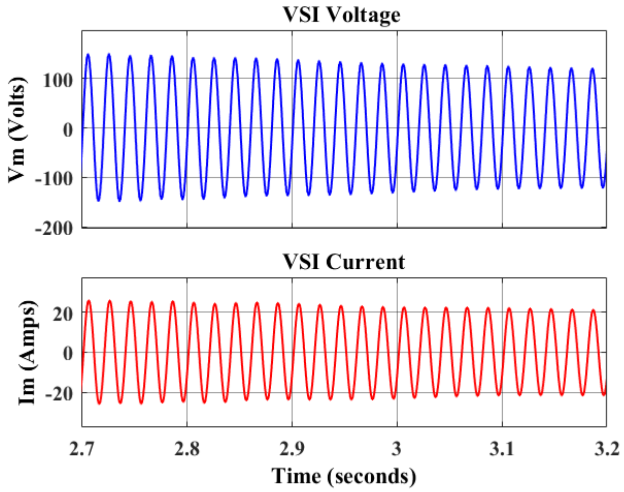

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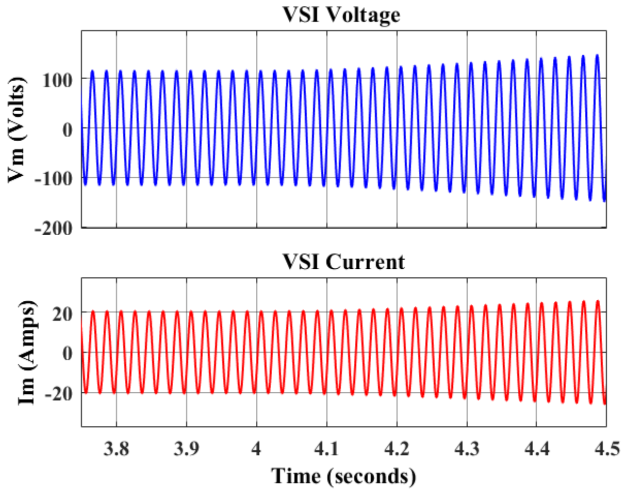

d)

Figure 13 VSI Voltage and Current in islanded mode

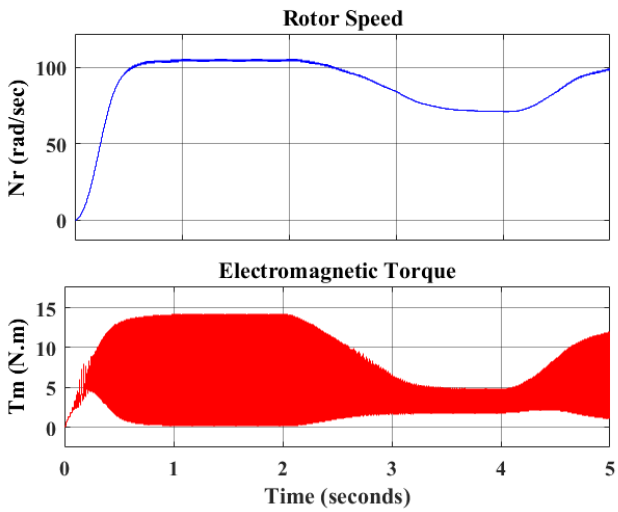

Figure 14 Motor speed and torque in islanded mode

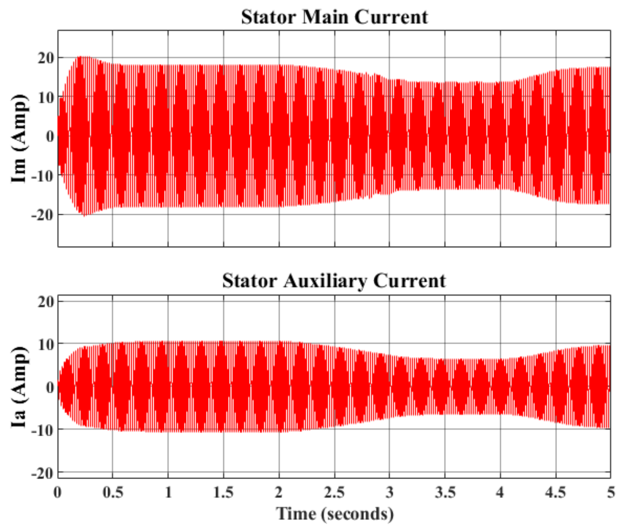

Figure 15 Motor main and auxiliary current in islanded mode

V. Conclusion

In conclusion, the discussions surrounding the reduced topology implemented in a solar water pump system for both grid-connected and islanded modes highlight several key findings. In the grid-connected mode, the system exhibits efficient solar power utilization, with the Perturb and Observe (P&O) MPPT algorithm ensuring optimal performance by consistently tracking the maximum power point of the photovoltaic (PV) array. The Phase-Locked Loop (PLL)-based grid control contributes to synchronized and stable integration with the utility grid, fostering bidirectional energy flow and reliable power supply to connected loads.

During islanded operation, the system's resilience is demonstrated as it operates independently from the grid. While the P&O MPPT algorithm remains effective, deviations in PV voltage and current under dynamic solar conditions indicate the potential for controller enhancements. The DC boost converter exhibits variation in its ability to track the reference DC link voltage during these changes, highlighting the need for a more robust controller design for standalone scenarios.

Additionally, results from motor speed and torque observations emphasize the system's adaptability to dynamic solar irradiation changes, making it suitable for water pumping applications. The sinusoidal nature of the VSI outputs, achieved through the designed LCL filter, ensures clean power generation. However, in islanded mode, deviations in motor speed during dynamic solar changes suggest room for improvement in maintaining speed consistency.

In summary, the reduced topology employed in this solar water pump system demonstrates promising performance in grid-connected and islanded modes. While the system exhibits effective power tracking and reliable operation, opportunities for enhancement, especially in controller robustness during islanded operation, should be explored for continued optimization and increased reliability in diverse solar conditions.

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REFERENCES

[1] C. Slabbert and M. Malengret, "Grid connected/solar water pump for rural areas," *IEEE International Symposium on Industrial Electronics. Proceedings. ISIE'98 (Cat. No.98TH8357)*, Pretoria, South Africa, 1998, pp. 31-34 vol.1, doi: 10.1109/ISIE.1998.707744.

[2] S. Ramos, Helena M. Ramos, Solar powered pumps to supply water for rural or isolated zones: A case study,Energy for Sustainable Development,Volume 13, Issue 3,2009,Pages 151-158,ISSN 0973-0826,https://doi.org/10.1016/j.esd.2009.06.006.

[3] M. T. A. Khan, M. R. Ahmed, S. I. Ahmed and S. I. Khan, "Design and performance analysis of water pumping using solar PV," *2nd International Conference on the Developments in Renewable Energy Technology (ICDRET 2012)*, Dhaka, Bangladesh, 2012, pp. 1-4.

[4] Rahul Rawat, S.C. Kaushik, Ravita Lamba, A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system,Renewable and Sustainable Energy Reviews,Volume 57,2016,Pages 1506-1519,ISSN 1364-0321

[5] R. Kumar and B. Singh, "Grid interfaced solar PV based water pumping using brushless DC motor drive," *2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Trivandrum, India, 2016, pp. 1-6, doi: 10.1109/PEDES.2016.7914298.

[6] R. Kumar and B. Singh, "Grid interfaced solar PV powered brushless DC motor driven water pumping system," *2016 7th India International Conference on Power Electronics (IICPE)*, Patiala, India, 2016, pp. 1-5, doi: 10.1109/IICPE.2016.8079369.

[7] U. Sharma and B. Singh, "Grid interactive bidirectional solar PV array fed water pumping system," *2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Trivandrum, India, 2016, pp. 1-6, doi: 10.1109/PEDES.2016.7914434.

[8] Sharma, U., Singh, B. and Kumar, S. (2017), Intelligent grid interfaced solar water pumping system. IET Renewable Power Generation, 11: 614-624. https://doi.org/10.1049/iet-rpg.2016.0597

[9] B. Singh and S. Murshid, "A Grid-Interactive Permanent-Magnet Synchronous Motor-Driven Solar Water-Pumping System," in *IEEE Transactions on Industry Applications*, vol. 54, no. 5, pp. 5549-5561, Sept.-Oct. 2018, doi: 10.1109/TIA.2018.2860564.

[10] Mansur Aliyu, Ghassan Hassan, Syed A. Said, Muhammad U. Siddiqui, Ali T. Alawami, Ibrahim M. Elamin, A review of solar-powered water pumping systems,Renewable and Sustainable Energy Reviews,Volume 87,2018,Pages 61-76,ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.02.010.

[11] J. V. Parmar, S. K. Reddy, B. Swaminathan, A. Mudlapur and B. Venkatesaperumal, "A Novel Back to Back Inverter Configuration for Solar Water Pumping and Grid-Tie Application," *2018 IEEE International Conference on*

Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Palermo, Italy, 2018, pp. 1-6, doi: 10.1109/EEEIC.2018.8494528.

[12] S. Murshid and B. Singh, "Analysis and Control of Weak Grid Interfaced Autonomous Solar Water Pumping System for Industrial and Commercial Applications," in *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7207-7218, Nov.-Dec. 2019, doi: 10.1109/TIA.2019.2939705.

[13] R. Kumar and B. Singh, "Grid Interactive Solar PV-Based Water Pumping Using BLDC Motor Drive," in *IEEE Transactions on Industry Applications*, vol. 55, no. 5, pp. 5153-5165, Sept.-Oct. 2019, doi: 10.1109/TIA.2019.2928286.

[14] Murshid S, Singh B. Power quality improvement in grid integrated solar water pumping system using Vienna converter. *Int Trans Electr Energ Syst*. 2019; 29:e12129. https://doi.org/10.1002/2050-7038.12129

[15] S. Rahman *et al*., "Design and Implementation of Cascaded Multilevel qZSI Powered Single-Phase Induction Motor for Isolated Grid Water Pump Application," in *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1907-1917, March-April 2020, doi: 10.1109/TIA.2019.2959734.

[16] Srinivasa Rao Mantri, Rama Sudha Kasibhatla & Venkata Krishna Bhanu Chennapragada (2020) Grid-connected vs. off-grid solar water pumping systems for agriculture in India: a comparative study, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, DOI: 10.1080/15567036.2020.1745957

[17] K. Mishra and B. Singh, "Grid Interactive Single-Stage Solar Powered Water Pumping System Utilizing Improved Control Technique," in *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 304-314, Jan. 2020, doi: 10.1109/TSTE.2018.2890670.

[18] A. Yalavarthi and B. Singh, "Grid-Integrated Solar PV Fed SRM Water Pump Drive for Small-Scale Irrigation and Household Supply," *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 3073-3078, doi: 10.1109/ECCE44975.2020.9236299.

[19] A. K. Mishra and B. Singh, "Grid-Integrated SRM-Driven Solar Water Pump With Power Flow Management," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 3, pp. 2723-2734, June 2021, doi: 10.1109/JESTPE.2020.3022835.

[20] Muralidhar K, Rajasekar N. A review of various components of solar water-pumping system: Configuration, characteristics, and performance. *Int Trans Electr Energ Syst*. 2021; 31(9):e13002. https://doi.org/10.1002/2050-7038.13002

[21] A. Lilhare, S. G. Kadwane and P. Fulzele, "Grid Supported Solar Water Pump System," *2021 Innovations in Power and Advanced Computing Technologies (i-PACT)*, Kuala Lumpur, Malaysia, 2021, pp. 1-5, doi: 10.1109/i-PACT52855.2021.9696889.

[22] A. Sharma, T. N. Gupta and M. S. Rawat, "Grid Connected Solar PV fed Constant Power Water Pumping System," *2021 International Conference on Intelligent Technologies (CONIT)*, Hubli, India, 2021, pp. 1-6, doi: 10.1109/CONIT51480.2021.9498459.

[23] V. V and J. P, "Control of Single-Phase Grid Connected Inverter Using Proportional Resonant Control Algorithm for Solar Water Pumping System," *2021 International Conference on Communication, Control and Information Sciences (ICCISc)*, Idukki, India, 2021, pp. 1-6, doi: 10.1109/ICCISc52257.2021.9484991.

[24] Shrey Verma, Shubham Mishra, Subhankar Chowdhury, Ambar Gaur, Subhashree Mohapatra, Archana Soni, Puneet Verma, Solar PV powered water pumping system – A review,Materials Today: Proceedings,Volume 46, Part 11,2021,Pages 5601-5606,ISSN 2214-7853,https://doi.org/10.1016/j.matpr.2020.09.434.

[25] A. K. Mishra, B. Singh and T. Kim, "An Efficient and Credible Grid-Interfaced Solar PV Water Pumping System With Energy Storage," in *IEEE Journal of Photovoltaics*, vol. 12, no. 3, pp. 880-887, May 2022, doi: 10.1109/JPHOTOV.2022.3147449.

[26] C. Manideep and M. V. Priya, "Improvement Of Performance In Grid Connected Solar Photovoltaic For Water Pumping System Using Induction Motor," *2022 International Conference on Business Analytics for Technology and Security (ICBATS)*, Dubai, United Arab Emirates, 2022, pp. 1-5, doi: 10.1109/ICBATS54253.2022.9759053.

[27] A. K. Mishra, B. Singh and T. Kim, "An Economical Solar Water Pump With Grid and Battery Backup for Continuous Operation," in *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 4, no. 1, pp. 109-117, Jan. 2023, doi: 10.1109/JESTIE.2022.3192212

[28] Kar, B.N., Samuel, P., Pradhan, J.K. and Mallick, A. (2024), "Grid-connected solar photovoltaic-fed brushless DC motor drive for water pumping system using colliding body optimization technique", *Circuit World*, Vol. 50 No. 1, pp. 18-34. https://doi.org/10.1108/CW-09-2021-0252