RESEARCH ARTICLE

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Designing and Implementation of Power Converter for Solar Pump to Drive Agriculture Load

Shweta Bansal[1*], R N Patel[2], Manoj K. Nigam[3], Viren M. Victor[4], Yugal Kishor[5] and Ruchira[6]

[1,3]Mahaveer Academy of Technology and Science University, Raipur, Chattisgarh, India.

[4]Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chattisgarh, India.

[2,5]National Institute of Technology, Raipur, Chattisgarh, India.

[6]Amity University, Lucknow, Uttar Pradesh, India.

Abstract

The increasing demand for energy, coupled with the need for sustainable solutions, has led to the exploration of solar energy as an alternative power source. Agriculture and domestic equipment operations are two key areas where solar energy can significantly promote energy efficiency and reduce carbon emissions. The primary objective of this research is to develop a solar pump controller that efficiently harnesses solar power for agricultural and domestic equipment operations. The controller aims to optimize energy utilization, enhance system reliability, and provide cost-effective solutions for end-users. The development of a solar pump controller can help reduce the environmental impact associated with conventional energy sources, improve energy efficiency, and promote sustainable practices. This article discusses the solar pump controller's key components, operational principles, and performance evaluation.

Keywords: Photovoltaic, Boost converter, H-bridge Inverter, Pulse width modulation technique, Arduino Uno, Duty cycle.

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Introduction

India is an agriculture-based country, and a major portion of its GDP comes from agriculture. Various equipment is used to accomplish agricultural and post-harvest operations. Farmers predominantly use draught animals like bullocks and buffaloes in Chhattisgarh. But agricultural work is seasonal and for a short period of time. These animals stand idle for the rest of the period. To utilize the bullock power during their idle period, various agricultural and domestic equipment like chaff cutters, flour mills, grinders, threshers, and mini dal and rice mills are operated with the help of bullock power.[1,2] A similar concept has been used in this paper. The domestic and agricultural equipment was run by bullock power, which has been replaced by idle solar pump power. Electricity is also generated for charging batteries using animal power, and to perform all these operations through bullock power, a system was developed called the "rotary mode gear system (rotary power transmission system).[3] Battery-operated sprayers, weeders, threshers, shellers, and much more equipment are developed using batteries charged using solar power-generated electricity. Solar-powered battery-operated irrigation pumps are also in use in different parts of the country.

Non-conventional sources of energy are in high demand in every nation because most human activity is based on energy. Like most developing countries, the energy situation is very critical. In order to avoid most atmospheric pollution, scientists are continuously developing green energy.[4] Among many alternative sources, solar energy has been considered to meet the growing demand for energy because India is the ideal location for abundant solar radiation. A noticeable amount of solar energy has been used in solar pumping systems to fulfill the water demand in the agricultural sector, especially in rural areas.[5]

Solar PV Pumps have become the backbone of India's rural agricultural regions. Almost every state government provides substantial subsidies and support for its implementation and use by farmers in order to eliminate crop water shortages.[6,7] However, such a system, which was deployed at a substantial expense, is currently utilized for approximately 150 days per year on average. To optimize the usage of the power

Corresponding Author: Shweta Bansal, Mahaveer Academy of Technology and Science University, Raipur, Chattisgarh, India, e-mail: agrawal4shweta@gmail.com1

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generated by the solar PV system, the controller supplied for the installation of the solar-based water pumping system is restricted to water pumping applications only. During or after crop harvest, such a vast solar energy system sits inactive beneath the brilliant sun.[8] Our research objective is to design and develop an efficient PV controller system that could facilitate free solar energy for various agricultural duties, including grinding, chaff cutting, oil extraction, pulverization, etc. This will enhance the agricultural sector's productivity and farmers' income. Using this technology, the system could be utilized effectively throughout the entire year. The work's objectives are as follows:

- Design and development of a smart operation (SSPC) for a solar pump system.
- Testing and evaluation of a developed solar pump controller to run different agricultural and domestic gadgets
- Feasibility testing of different agricultural and domestic equipment with a developed smart system for their operation.

The Solar water pumping system is deployed at a huge cost to the farmer, the exchequer, or the government. Besides the SPV panels, which last for 25 years, other constituents of the solar pumping system must have the design and quality to last that many years.[9] Keeping both these aspects in mind, the Controller design should be such that, besides the water pump, it should be able to run any agrarian equipment that will help farmers raise the productivity and quality of their produce and save diesel or another form of fossil-based energy. The controller design should also incorporate features that will consider degradation in the panels and other factors like partial shading, etc. Figure 1 shows the block diagram of the proposed system.

The block diagram consists of five main blocks: the PV module, boost converter bridge inverter, Induction motor, and the micro-controller unit, with a PWM controller module extracting the sunlight, which converts it into electrical energy and feeds it to the boost converter.[17] Meanwhile, the voltage and current of the PV output are sensed and given to the microcontroller. The microcontroller has been

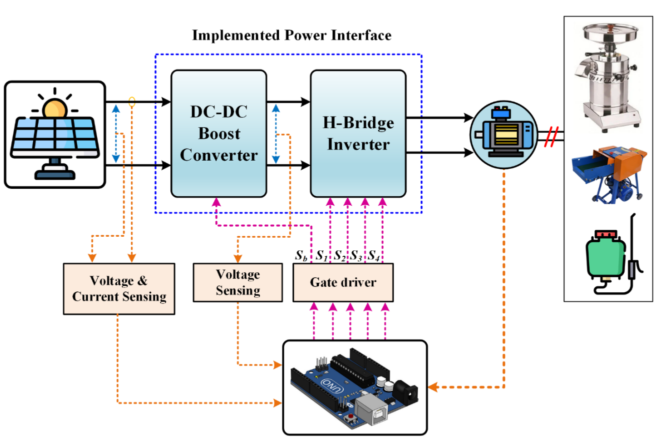

Figure 1: block diagram of the proposed system

programmed based on the PWM technique that controls the duty cycle of the boost converter to obtain optimum power at all conditions. Then the H-bridge inverter converts the DC voltage into AC, which is then fed to the induction motor to drive the load. A microcontroller controls the switching pulse of both the boost converter and H-bridge inverter.

Considering past observations, the maximum solar water pumping installation is running for 140 to 160 days a year, and for the remaining days, it is sitting idle. This is the underutilization of infrastructure (PV, PV structure, controllers, etc.).[10] The controller provided for installing solar pumping systems should be multifunctional to maximize the benefits of solar photovoltaics for the agricultural industry and the farmer's bottom line. Such a controller would allow the solar system to be operational more than 300 days a year. When irrigation is not necessary, the controller should let the farmer use other equipment, such as a thresher or winnower, to clean his crop, cut chaff for milk animals, run cold storage to preserve his crop or a deep freezer to store agrarian or dairy goods, and so on. The farmer's diesel expenditures will be reduced, he'll receive a greater price for his crops at market, and his income will increase dramatically as a result. The proposed work will provide us with many advantages, such as: Tapping the untapped solar energy available.

1. Extra income for farmers
2. Reducing manual efforts
3. Using tapped energy to run agricultural and domestic implements
4. Power backup for emergencies or multiple uses

Solar pump controller design

Applying efficient topologies can enhance the energy conversion topology in solar PV systems. In solar PV systems, there is variation in voltage, which can be withstood by using power electronic devices such as DC-DC boost converters and inverters.[11]

Conventional boost converters consist of inductors that are connected either in series or parallel. Its performance is very poor for high-voltage and high-current applications.[12] It requires a high duty ratio for high voltage levels but will cause high switching losses that are high dv/dt losses. Large ripple currents can be limited by the use of an inductor. The use of inductors and switches can achieve high voltage conversion gain. Moreover, the boost converter causes weak control when it is coupled to PV panels during large variations in input voltage. Better results can be obtained when the output voltage is not higher than the input voltage. Various studies have been done in boost converters to obtain high voltage gain for the different combinations of diode-inductor-capacitor configurations that have been used.

Zero voltage and zero current switching were introduced in a boost converter with multiplier cell voltage.[13,14] The combination of coupled inductor and multiplier cells eliminates different issues, like high pulse current. The boost converter provides decent performance in continuous conduction mode. An EMI filter is installed at the input for discontinuous conduction mode to eliminate noise.[15,16] The duty cycle should be shorter to eliminate switching losses. Controller design consists of

1. Use the pulse width modulation technique to control the duty cycle.
2. Designing and analyzing boost converters for high voltage gain.
3. Designing an inverter for continuous conduction
4. Use the output of the boost converter and inverter to run the load.
5. Calculate the mathematical model of the proposed system.
6. Validate the proposed system experimentally.

This controller design can be used in actual solar pumps and to drive various load applications. Figure 2 shows the configuration of the proposed solar PV system with a boost converter and H-bridge inverter-fed induction motor. The PWM technique is used in the power optimization of solar PV systems.[18] Using the PWM technique, the pulse generator generates a high-frequency signal for the boost converter at an optimized duty cycle value. The high switching frequency means low values for other components. The four switching pulses are used to operate the H bridge inverter. The design of the proposed system is elaborated on in the following section.

Photovoltaic model

The photovoltaic cell produces DC current from sunlight. Solar cells are connected in series-parallel combinations to generate a PV array's required voltage and current. The generated power depends on the intensity of sunlight, cell temperature, dust, shadow, and so on.[19,20] Here, a solar PV array of 1 kW has been taken, which is somewhat more than required by the motor for the experiment to overcome the effects caused by the losses associated with the converter and motor.

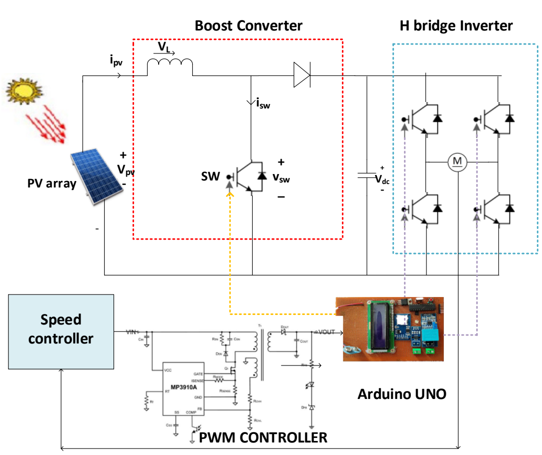

Figure 2: Proposed circuit diagram of the boost converter fed single phase IM drive system

DC-DC high gain converter

The generated voltage of the PV panel fluctuates for boosting and maintaining a constant voltage boost converter used. In this experimental setup, IGBT has been used for an off-switching cycle to gain the desired voltage. The pulse width modulation technique has been used to control the duty cycle. The control pulses that have been given to IGBT are generated by a microcontroller. The generated voltage of the PV array is 90V which is further boosted to 220V by the boost converter.

Boost converter consists of an inductor, electronic switch device diode, and output filter capacitor.[21-23] It basically operates in two modes based on the opening and closing of switches.in mode one when the switch is on, the diode is off then the current passes through the inductor, and energy has stored on it. In mode 2 when the switch is off the voltage that appears across the load is the sum of the voltage across the inductor and the supply voltage.[24] The output voltage across the boost converter is given by

$V_o = V_{in}/(1\text{-}D)$ (1)

Where "D" is the duty cycle of the switch,

$D = t_{on}/T$ (2)

$T = 1/f_s$ (3)

V_o: the gained output voltage of supplied power.
V_{in}: supplied power from available sources.
ton: switch on period.
T: switching period.
f_s: supply frequency.
L: inductor value.
C: capacitor value
f_{sw}: switching frequency

The design of the boost converter is basically based on four components: an inductor, capacitor, diode, and switches. The parameters and their values related to the boost converter circuit is shown in Table 1 and design formulas and values of L and C are listed in Table 2.

Minimum duty cycle $= 1 - V_{in}(max)/V_o(min)$ (4)
$= 1\text{-}\ 99/150$
$= 34\%$

Maximum duty cycle $= 1 - V_{in}(min)/V_o(max)$ (5)
$= 1 - 60/220$
$= 72.7\%$

$$\text{Minimum inductor size } Lmin = \frac{D*Vin*(1-D)}{fsw*2*Iout} \quad (6)$$

$$Lmin = \frac{0.34*90*(1-0.34)}{10*10^3*2*10}$$

$$L_{min} = 100.98\mu H$$

$$I_L\ peak = \frac{Vin\ max*D}{fsw*L}$$

$$= 30.30A$$

Table 1: Specifications for design of boost converter

Parameter	*Value*
f_{sw}	10kHz
V_{in} (min)	60V
V_{in} (max)	99V
V_o (min)	150V
V_o (max)	220V
I_{out}	10A
V_o (ripple)	0.5Vor 5%

Table 2: Component Values for boost converter

Name of the component	*Design formula*	*Calculated value*
Lmin	$\frac{D * Vin * (1 - D)}{fsw * 2 * Iout}$	100.98µH
Cmin	$\frac{Iout}{Vripple * fsw}$	2000µf

$$\text{Minimum Capacitor } Cmin = \frac{Iout}{Vripple * fsw} \quad (7)$$

$$Cmin = \frac{10}{0.5 * 10 * 1o^3}$$

$$C_{min} = 2000\mu f$$

Experimental setup

Figure 3 shows the experimental setup of the proposed system. The setup consists of a power circuit and a control circuit. The power circuit has a PV panel substitute, boost converter, H bridge inverter, and induction motor through which any load can couple. The control circuit comprises a microcontroller to control pulses in the IGBT of the boost converter and switches of the H bridge inverter through pulse width modulation techniques.

Result and Discussion

The implemented power electronics interface is validated through a developed experimental setup. The complete hardware setup for the implemented system is demonstrated in Figure 3, which consists of a front-end DC-DC boost converter connected to a programmable power supply and an end single-phase H-bridge inverter connected to an induction motor. The programmable power supply replicates the solar photovoltaic (SPV) panel by providing a similar output voltage profile. Here, the front-end DC-DC boost converter increases the output voltage level since SPV has weather-dependent output. Therefore, this converter stabilizes the intermediate DC voltage level. This DC stage is then fed to the H-bridge inverter, which converts DC into AC to drive the induction motor. The implemented system is developed to run a 1 kW load. The 90V input voltage is the typical voltage level of three SPV panels applied to the DC-DC boost converter. This converter increases the voltage level to 220V at the intermediate DC bus. The output voltage of the boost converter is adjusted by varying the duty ratio (D) of the power IGBT. The D is adjusted such that the boost converter is able to maintain the desired voltage level at its output. The intermediate DC-bus is given as input to the H-bridge inverter to convert it into a 220V AC supply to drive a single-phase induction motor coupled with any agricultural load.

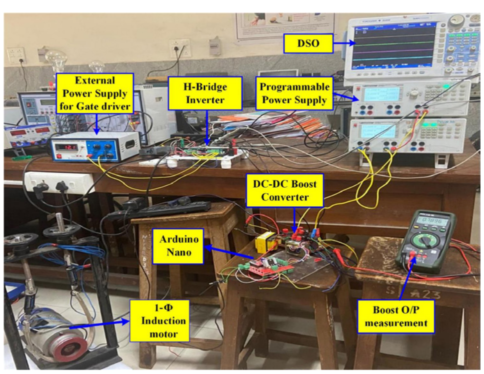

Figure 3: Experimental setup in the laboratory

The Arduino Uno runs the whole control algorithm for the system and motor. High-gain DC-DC converter components include a quick recovery diode, capacitor, coil, and insulated-gate bipolar transistor. A voltage sensor measures the PV voltage signal and reports its readings to the controller circuit through the analog-to-digital converter channel.

A 1 kW laboratory prototype circuit has been developed and tested to obtain high voltage gain and validate theoretical analysis and performance anticipation, as illustrated in Figure 3. The nominal input voltage V_{in} is 90V, and the boost converter regulates the voltage to 220V. The frequency of operation is 10 kHz. The minimum value of the D is set to 34%, and the maximum value is 72.7%, to minimize the switching losses.

The multimeter determines the actual voltage and current being used by the motor by taking into account all of these factors. Following this step, the reference current and the current that was computed are compared, and then the gate signal is generated. The firing signal for the boost converter and inverter is provided by the control signal generated in the Arduino Uno through pulse width modulation techniques. Pulses have been produced for the microcontroller, as can be seen in Figure 4. The frequency has been maintained at 9.43 kHz throughout this process. The gate drive of the IGBT that is part of the boost converter and inverter has been supplied with that firing pulse.

In this experiment, three solar panels are connected in series. In this arrangement, the generated voltage is 90 volts, which is too low for running any motor. This voltage is boosted to 220 volts by a boost converter, as shown in Figure 5. Pulse width modulation techniques have been used in this boost converter. Voltage cannot be boosted more than 3 to 4 times the input voltage because it will increase switching loss, which is not feasible practically.

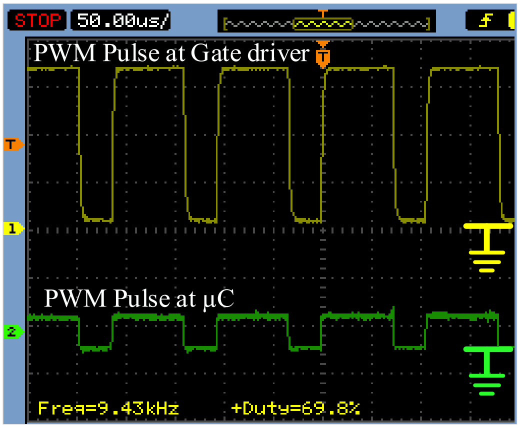

Figure 4: PWM pulse of microcontroller and gate driver

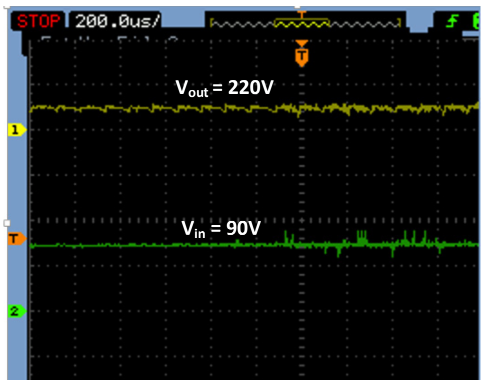

Figure 5: Boost converter input and output voltage

Figure 6 represents tie diode voltage. When the switch is on no current will flow through diode but in off period diode will be in conduction mode. Figure 7 shows the inductor current when switch is on energy has stored in the inductor so the current increases linearly not exponentially and when switch is off inductor discharge energy so the current decreases. Figure 8 shows the output current of boost converter which is sum of the inductor current and capacitor current.

The output of the boost converter is the input of the inverter. The inverter converts the dc signal to ac as shown in Figure 9. It is used because most of the appliances work on ac. As shown in Figure 10, 4 switching pulses have been given to the inverter. Switching pulses have been given simultaneously to switches 1, 3, and 2. As shown in Figure 10, there is some time delay between switching switches 1, 3, and 4. Switch 3 starts after a microsecond of switch 1, and Switch 4 starts after a microsecond of switch 2. This is the general phenomenon of the working of an inverter. The intermediate DC-bus is given as input to the H-bridge inverter to convert it into a 220V AC supply to drive a single-phase induction motor drive coupled with any agricultural load. Figure 11 shows the voltage across the various inverter switches.

Other Photovoltaic applications in the field of agriculture

Solar-based pump is an eco-friendly and economical replacement for traditional pump running on electricity and

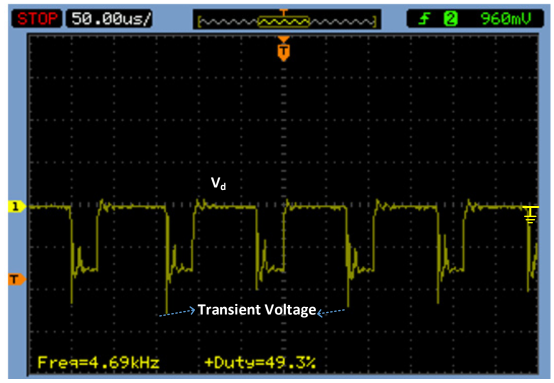

Figure 6: Diode voltage

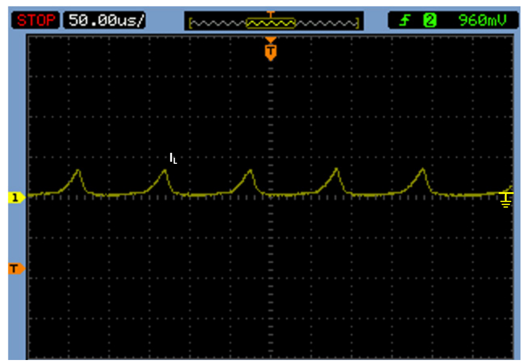

Figure 7: Inductor current

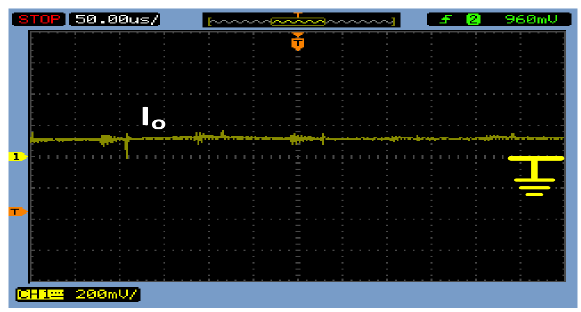

Figure 8: Output current of the boost converter

fossil fuel. They can be used in a variety of applications, such as in agriculture, livestock, domestic use, community water supply, and water treatment. Overall solar pump reduces fossil fuel dependency and provides water access in isolated places.

The idle solar pump energy can be used in other agriculture applications such as

- Portable solar-powered lights – Farmers can use these lights to work their fields after dark.
- Solar power weather station – The solar power weather station can monitor temperature, humidity, rainfall, wind speed, and other weather conditions. This information can be used to make decisions about when to plant fertilize and harvest.
- Solar power insect trap – A solar power insect trap can be used to attract and trap pests that can damage crops.

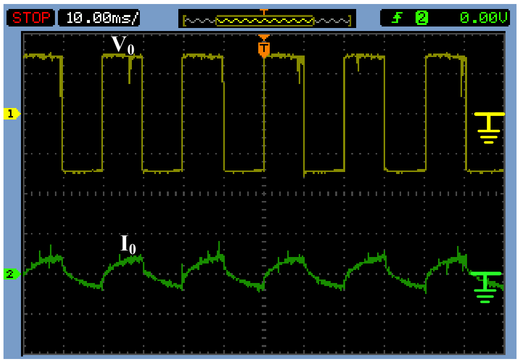

Figure 9: Inverter output voltage and current

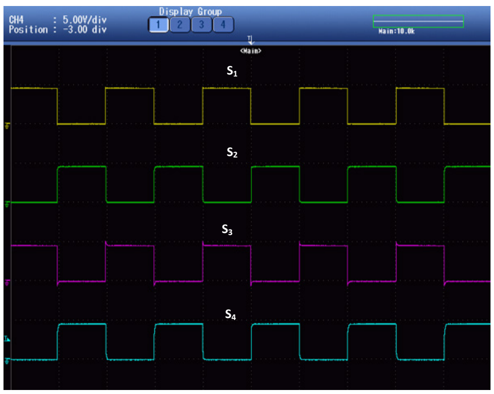

Figure 10: Inverter switching pulses

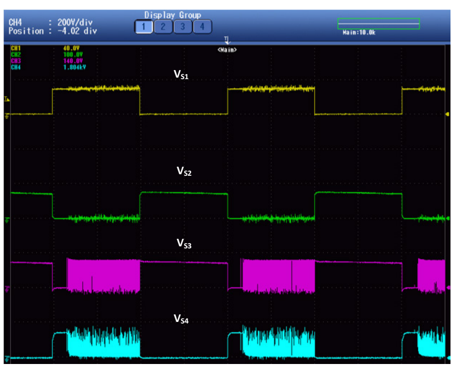

Figure 11: Voltage across the Inverter switches S_1, S_2, S_3, and S_4

- Electric seeding machine – This device can be used to facilitate the planting seeds in agricultural fields. There are different types of electric seeding machines which are either connected through tractors or other agricultural equipment.
- Wheat flour machine – A wheat flour machine uses for grinding wheat. It is normally used for commercial purposes.
- Electric sprayer pesticide machine – This machine is used to apply liquid pesticides, herbicides, or fertilizers to crops or plants.
- Oil mill – An oil mill is a machine that is used to extract oil from various types of seeds and nuts. These machines are used for commercial purposes.

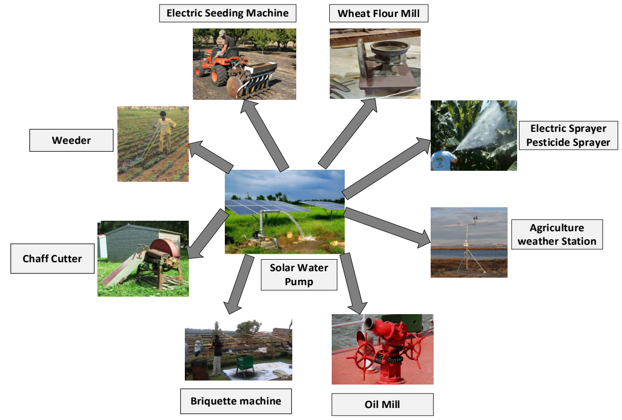

Figure 12: Application of PV in the agriculture sector

- Electric cleaner – This machine can be used to clean surfaces through high-pressure water to remove dirt.

Conclusion

In this paper, PV fed induction motor drive for a water pumping system based on a boost converter and H-bridge inverter. The proposed system enhances 3 times the output PV voltage. The boost converter is connected to the source end and the H bridge inverter is connected to the load end. The integration of a boost converter and induction motor on a PV array for water pumping has emerged as a feasible solution in the context of simplicity, economics, compactness, efficiency, reliability, and availability. The proposed system has been tested in the laboratory in different solar irradiance. First, power devices and control systems have been designed and assembled successfully. After testing in the laboratory, this system was assembled in the field with a solar pump.

The experimental findings indicate the operational efficacy of the implemented system to tap the unutilized solar power available during the non-pumping period of pre-installed solar pumps at agricultural fields. This system optimizes the available solar power and increases the utility of existing solar pumps by driving the other agricultural loads, which are typically run by diesel engines or required utility grids. Therefore, the implemented system enables distributed solar photovoltaic generation to drive the typical agricultural loads while reducing carbon footprints.

References

[1] Phaniraja, K.L. and Panchasara, H.H., "Indian Draught Animals Power", Veterinary World, Vol.2(10), pp 404-407,2009.

[2] Amit Namdeo, Navneet Kumar Dhruwe and VM Victor, "Utilization of draught animal power source for sustainable agriculture- A review"; Journal of Pharmacognosy and Phytochemistry 2019; 8(6): 2422-2426.

[3] D. BEHERA, M.K. GHOSAL, A.K. MOHAPATRA (2012). All India Coordinated Research Project on Utilization of Animal Energy With Enhanced System Efficiency, Coordinator of AICRP on UAE, pp 1-17.

[4] N. H. Agarwal and B. B. Pimple, "Solar photovoltaic array based

brushless DC motor for fans in Indian railways using maximum power point tracking algorithm," *2015 39th National Systems Conference (NSC)*, Greater Noida, India, 2015, pp. 1-6, doi: 10.1109/NATSYS.2015.7489122.

[5] M. Archana, J. A. Thulasi and M. B. J. Ananth, "An efficient solar power based four quadrant operation of BLDC motor," *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, Chennai, India, 2016, pp. 4841-4846, doi: 10.1109/ICEEOT.2016.7755640.

[6] 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.

[7] J. J. O. Vergara and T. L. Vergara, "PWM Speed Control of Brushless DC Motor for Inrush Current Regulation of Solar Water Pumping System," 2021 IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), Manila, Philippines, 2021, pp. 1-5, doi: 10.1109/HNICEM54116.2021.9732039.

[8] A. B. Kancherla and D. R. Kishore, "Design of Solar-PV Operated Formal DC-DC Converter Fed PMBLDC Motor Drive For Real-time Applications," 2020 IEEE International Symposium on Sustainable Energy, Signal Processing and Cyber Security (iSSSC), Gunupur Odisha, India, 2020, pp. 1-6, doi: 10.1109/iSSSC50941.2020.9358813.

[9] K. Remya and M. Shahin, "Switched Capacitor Converter for Solar Powered BLDC Motor Driven Water Pump," *2019 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*, Kannur, India, 2019, pp. 145-150, doi: 10.1109/ICICICT46008.2019.8993266.

[10] R. Kumar and B. Singh, "Single Stage Solar PV Fed Brushless DC Motor Driven Water Pump," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 3, pp. 1377-1385, Sept. 2017, doi: 10.1109/JESTPE.2017.2699918.

[11] Mohammed Ali Khan, Ahteshamul Haque, Varaha Satya Bharath Kurukuru, Frede Blaabjerg,"Optimizing the Performance of Single-Phase Photovoltaic Inverter using Wavelet-Fuzzy Controller",e-Prime - Advances in Electrical Engineering, Electronics and Energy,Volume 3,2023,100093,ISSN 2772-6711,https://doi.org/10.1016/j.prime.2022.100093.

[12] Elbarbary Z.L. Salem, "High Gain Boost Converter fed asynchronous motor drive for water pumping system"; International Journal of Electronics; pp 1097-1116, https://doi.org/10.1080/00207217.2021.1966663 , 2021.

[13] A. H. Chander and L. Kumar, "Design of a synchronous reference frame controller for single phase standalone photovoltaic inverter," in *2017 14th IEEE India Council International Conference (INDICON)*, 2017.

[14] K. Harsh and VIT, IIST, "BLDC motor driven water pump fed by solar photovoltaic array using boostconverter," *Int. J. Eng. Res. Technol. (Ahmedabad)*, vol. V9, no. 06, 2020.

[15] G. Makarabbi, V. Gavade, R. Panguloori, and P. Mishra, "Compatibility and performance study of home appliances in a DC home distribution system," in *2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2014.

[16] R. K. Sahu and B. Shaw, "Design of type 2 fuzzy logic controller-based inverter for isolated PV system," *Helix*, vol. 10, no. 2, pp. 48–52, 2020.

[17] M. Archana, J. A. Thulasi and M. B. J. Ananth, "An efficient solar power based four quadrant operation of BLDC motor," *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, Chennai, India, 2016, pp. 4841-4846, doi: 10.1109/ICEEOT.2016.7755640.

[18] R. Kumar and B. Singh, "BLDC motor driven water pump fed by solar photovoltaic array using boost converter," *2015 Annual IEEE India Conference (INDICON)*, New Delhi, India, 2015, pp. 1-6, doi: 10.1109/INDICON.2015.7443676.

[19] C. N. M. Ho, "Challenges and design considerations of PV inverters in the future smart grids," *9th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2012)*, Hong Kong, 2012, pp. 1-6, doi: 10.1049/cp.2012.2142.

[20] S. Patel and K. V. S. Rao, "Social acceptance of solar energy technology in India," *2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS)*, Nagercoil, India, 2016, pp. 142-147, doi: 10.1109/ICEETS.2016.7582914.

[21] R. K. Sahu and B. Shaw, "Design and simulation of a grid-integrated solar system PI based on MPPTcontroller using SCA optimized," in *Green Energy and Technology*, Singapore: Springer Nature Singapore, 2022, pp. 105–115.

[22] Y. Kishor and R. N. Patel, "Thermal modeling and reliability analysis of recently introduced high gainconverters for PV application," Cleaner Energy Systems, no. 100016, p. 100016, 2022.

[23] R. Galvin, "Identifying possible drivers of rebound effects and reverse rebounds among households with rooftop photovoltaics," *Renew. Energy Focus*, vol. 38, pp. 71–83, 2021, doi: 10.1016/j.ref.2021.06.002.

[24] Ruchira, Patel, R.N., Sinha, S.K. (2019). Performance Analysis of PV System Integrated with Boost Converter for Low Power Applications. In: Kumar, M., Pandey, R., Kumar, V. (eds) Advances in Interdisciplinary Engineering . Lecture Notes in Mechanical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-13-6577-5_85.