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A hybrid PV/utility powered irrigation water pumping system for rural agricultural areas

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Abstract: Pakistan is primarily an agriculture country with the capability of producing wheat, cotton, sugarcane and rice, which together are more than 75% of the total crop output. Underground water is the main source of irrigation. Most of the water pumps use diesel generator while others run on electricity. The diesel is very expensive and electric supply situation is very unreliable in Pakistan. Photovoltaic (PV) powered water pumps are an attractive alternative solution, but due to the high cost of solar panels, they are not within the reach of a common farmer. In this paper, a novel architecture for an irrigation water pump, simultaneously powered by utility and PV panels, is proposed. No battery backup is required. The system employs maximum power point tracking. The pump controller receives a single control input to produce desired water flow rate and concurrently maximizing the utilization of PV resource. The proposed solution allows the farmer to incrementally add solar panels to an existing grid powered pumping system, thereby reducing the initial investment required for full solar deployment. The investment in the partial deployment of solar panels is paid back to the farmer in reduced electricity tariff.

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PUBLIC INTEREST STATEMENT

Water is a significant resource for the social, economic and sustainable development of developing countries like Pakistan. Agriculture is a backbone of Pakistan's economy. The timely availability of water is critical for food crop production. The average availability of electricity from the grid is around 8–12 h per day in rural agriculture areas. Most of the water pumps use diesel generator while others run on electricity. The diesel is costly and electric supply situation is very unreliable. Therefore, food crop production is becoming a major concern due to insufficient rainfall and load shedding. The stand-alone solar powered water pumps are too expensive for most farmers. The objective of this research is to provide a reliable and economical solution for water pumping. A novel hybrid solar/utility powered irrigation water pumping system is investigated in this research. The solution works with any installed solar capacity with existing grid powered pump, thus reducing initial investment, while decreasing their long-term energy costs, thus balancing economic development and environmental sustainability.

Subjects: Renewable Energy; Electronics; Industrial Electronics; Power Electronics; Power Engineering; Systems & Controls; Circuits & Devices

Keywords: economics; farmers; flow rate; hybrid power system; maximum power point tracking; Pakistan; pump controller; solar energy; water pumping

1. Introduction

Water is a significant resource for the social, economic and sustainable development of Pakistan. From this perspective, the irrigated agriculture is of great importance in the socioeconomic life of the country. The agriculture is a major occupation in Pakistan. The agriculture in Pakistan largely depends upon irrigation. In Pakistan, the irrigated terrains supply more than 90% of the total agriculture production. It accounts for about 24.9% of GDP and employs around 49% of the labor force, according to Punjab Irrigation and Power Department (http://irrigation.punjab.gov.pk). The need of food grains is increasing day by day due to population growth. The role of the farmer is important in improving the food grain situation. So, farmers need to be supported in all aspects. The availability of water in time is crucial prerequisite for crop production to meet the agriculture needs. Due to insufficient rainfall and load shedding, food crop production is becoming a major problem in Pakistan.

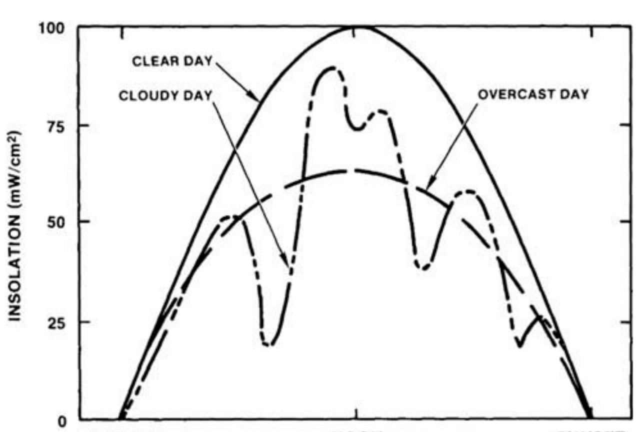
The government of Pakistan has taken up many irrigation projects to provide barrage and canal irrigation, but due to geographical location, the coverage area is limited. According to the Alternative Energy Development Board, Government of Pakistan, (http://www.aedb.org) around one million agriculture tube wells are in operation at present and nearly 30% are operated by the national electric grid. It consumes approximately 15–20% of the total energy delivered by the electric grid. Due to power shortage in Pakistan, Government of Pakistan is increasing electricity price for agriculture tube wells. The average availability of electricity from the grid is around 8–12 h per day in rural remote areas. Due to the current energy crisis and high electricity tariff, the agriculture sector in Pakistan having groundwater as the source of irrigation is badly affected. Therefore, an efficient, reliable and cost-effective energy solution for the agriculture sector in Pakistan is needed for irrigation.

The solar water pumping system is the promising solution for irrigation. It is a clean, environmentally friendly and reliable source of supplying water that requires low maintenance. It has no running cost and long life as compared to a diesel generator. The amount of power extracted directly from solar panels is not sufficient, in terms of voltage and current, for running water pumping motor. The power electronic converter plays important role in system configuration. Different power electronic converters are used for maximum energy harvesting. The maximum power point tracking (MPPT) is used for extracting maximum energy from photovoltaic (PV) panels. MPPT is a not a physical tracking mechanism but an electronic method to operate PV panel at the optimal point. The DC–DC converter is employed for MPPT. The single stage water pumping configurations require the only inverter connected directly with PV panel cutting the cost of DC–DC converter. However, the inverter is responsible for both motor speed control and MPPT. A low cost and high-efficiency converter is proposed by Caracas, De Carvalho Farias, Teixeira, and De Souza Ribeiro (2014) for autonomous solar water pumping system. Another important factor is the use of batteries for storing energy in solar water pumping system. The system with batteries is not considered a promising solution as the batteries require regular maintenance and increase the system cost. There are currently three different pumping configurations that are mostly used:

1. DC drives with positive displacement pumps.
2. AC drive powering induction motor/centrifugal pump.
3. AC drive powering a three-phase permanent magnet synchronous motor.

The selection criteria of motors depend on various factors including cost, compatibility and efficiency. The first-generation PV pumps incorporated permanent-magnet DC motors, for low-to-medium head applications. However, the DC motor is not a suitable candidate for water pumping due to its commutator and brushes arrangement. Furthermore, the initial and maintenance costs of DC motor are higher. The induction motor is suitable for solar water pumping considering disadvantages of DC motor. Nowadays, induction motor driven by variable speed inverter is a standard motor for solar water pumping applications. This is because of its simplicity, low price and robustness compared to DC motor (Vitorino, De Rossiter Corrêa, Jacobina, & Lima, 2011). In the last 5 years, the electronically commutated brushless DC motors have also been used in solar pumping applications because it requires less maintenance (Kumar & Singh, 2017). Recently, a permanent magnet synchronous motor has been employed for PV water pumping system (Antonello, Carraro, Costabeber, Tinazzi, & Zigliotto, 2017). It has high torque density, high efficiency and small size. But it requires special magnetics design and is quite expensive. Switched reluctance motor has been reported in the literature for solar water pumping system (Singh, Mishra, & Kumar, 2016). However, it requires complex control and generates high noise. The centrifugal and positive displacement pumps are commonly used in solar water pumping systems. The centrifugal pumps are widely used due to their robustness, simplicity and low maintenance requirement (Elrefai, Hamdy, ElZawawi, & Hamad, 2016). In solar powered water pumping system, the sun irradiance can change due to climate conditions. The level of insolation for the clear, cloudy and overcast day is shown in Figure 1 (Thomas, 1987). During the cloudy season when the insolation level is low, the motor stops pumping water due to low power. The literature survey indicates that AC motor with a variable frequency inverter is optimized at low speed during low irradiation (Eskander & Zaki, 1997; Santiago-Gonzalez, Cruz-Colon, Otero-De-Leon, Lopez-Santiago, & Ortiz-Rivera, 2011). The various control algorithms, different types of power electronic converters and motors are proposed by the researchers in order to improve system reliability, efficiency and performance, while decreasing cost and complexity (Al-Badi et al., 2018; Antonello et al., 2017; Ashhab, 2008; Asumadu-Sarkodie, Sevinç, & Jayaweera, 2016; El-Shimy, 2013; Franklin, Cerqueira, & De Santana, 2014; Khatib, Mohamed, Sopian, & Mahmoud, 2013; Narayana, Mishra, & Singh, 2017; Rehman & Sahin, 2016; Rezk, 2016; Sawle, Gupta, & Kumar Bohre, 2016; Sharma, Kumar, & Singh, 2016; Singh et al., 2016). However, these studies have not considered the performance and control of hybrid utility–solar PV water pumping system. In this regard, a novel hybrid water pumping system is presented and investigated in this research. The overall objective of the proposed system is to drive a water pump partially powered from PV while taking the remaining power from the grid. If utility power is not available, due to load shedding, which is a very common scenario in rural areas in developing countries, the pump will run from available solar power at a reduced flow rate. If the PV power is not available, due to cloudy weather, then the motor will take all the required power from the utility. The advantage of mixing power from the utility and solar panels is twofold; initial investment is lower and the electricity cost from the grid is reduced proportionally to the amount of installed PV capacity.

Figure 1. Typical daily variations in solar radiation



2. Description of proposed water pumping system

The proposed system is shown in Figure 2. In the proposed systems, each PV panel output is extracted through a MPPT DC/DC converter in order to get maximum power from PV panels. If the sun irradiation on one PV panel decreases, it does not affect other solar panels, because each PV panel has an independent MPPT controller, thus avoiding partial shading effects. Utility AC power is converted to DC by a three-phase rectifier. The outputs from DC/DC converter and three-phase rectifier are connected to common DC bus. This DC voltage is used to drive a three-phase voltage source inverter, which provides the power to the motor. The motor speed is regulated for a given flow rate using variable frequency inverter. This is an efficient way of driving motor according to desired flow rate. At daytime, solar power is utilized, and utility power is saved, thus saving electricity bill. So, an optimal way is developed and tested to drive motor, partially powered by solar panels, while taking remaining power from the utility.

The combined utility and solar powered pumping system is the best solution for varying insolation. When the insolation level decreases, the MPPT tracks the new maximum power point (MPP) and utility supplies the remaining power for required power demand. When the insolation increases, the MPPT tracks the new MPP, and in this case, power from utility decreases. If solar power is zero, then the motor will run on utility power.

2.1. Design of DC–DC converter

A flyback converter is used for implementing MPPT. The flyback converter is derived from the buck–boost converter and provides isolation between input and output voltage. The turn ratio of the transformer provides increased design flexibility in the transfer relationship. A 500-W PV panel is used as the input of the converter. The transformer equivalent circuit that includes the magnetizing inductance L_m is shown in Figure 3 (Hart, 2011).

The flyback converter is designed based on specifications shown in Table 1. The value of magnetizing inductance is selected to ensure that flyback converter always operates in continuous conduction mode (CCM). The minimum value of magnetizing inductance required for CCM operation is (Hart, 2011)

$$(L_m)_{min} = \frac{(1-D)^2 R}{2f}\left(\frac{N_1}{N_2}\right)^2 \quad (1)$$

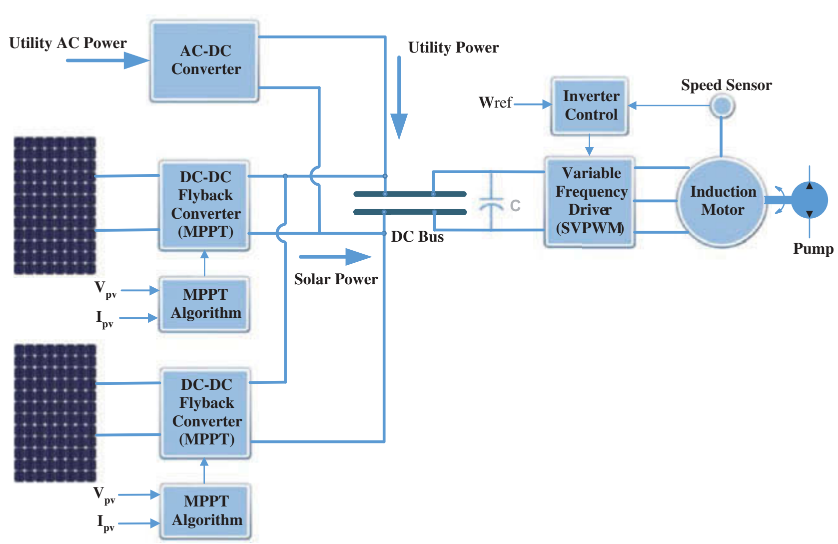


Figure 2. The proposed hybrid PV and utility powered water pumping system

Figure 3. The equivalent circuit of flyback converter

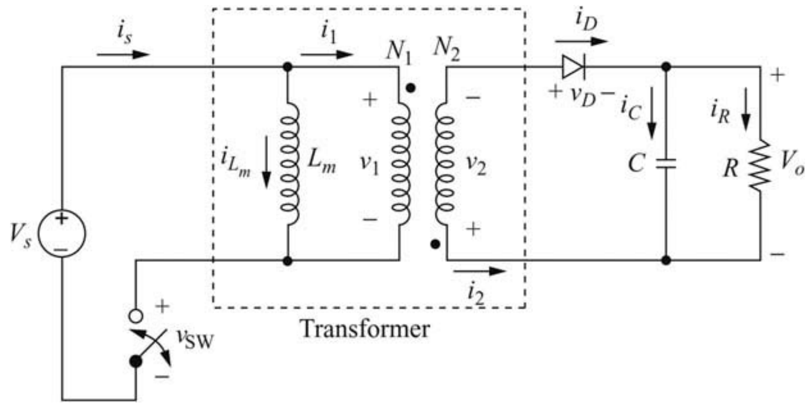


Table 1. Parameters of flyback converter		
Description	**Parameters**	**Nominal values**
Input voltage	V_s	0–74.6 V
Input current	I_s	0–8.6 A
Output power	P_o	500 W
Nominal output voltage	V_o	540 V
Output current	I_o	0 ~ 0.925 A
Switching frequency	f_s	20 kHz
Duty cycle	D	0.1 ~ 0.8
Magnetizing inductance	L_m	50 µH
Capacitor	C	100 µF

$$(L_m)_{min} = \frac{(1-0.1)^2}{2 \times 20kHz} \times \frac{560}{0.8928}\left(\frac{1}{20}\right)^2$$

$$(L_m)_{min} = 31.75\ \mu\text{H}$$

The flyback converter will operate in discontinuous conduction mode when power demand at the output is very low. The value of output capacitor is computed to ensure that output voltage ripple does not exceed 5% of the average output voltage.

$$\frac{\Delta V_o}{V_o} = \frac{DR}{RCf} \tag{2}$$

2.2. Modeling of PV cell and maximum power point tracking

The equivalent electric circuit of PV cell is used to study and model the input–output characteristic of the solar cell. A typical equivalent circuit model of PV cell is shown in Figure 4 (González-Longatt, 2005). The model comprises a current source, a diode and series resistance. This does not consist of parallel resistance because its effect is very small. The temperature effect on diode saturation current I_o is included in this model. The effect of temperature on photo current I_L is also included in the model (González-Longatt, 2005).

The total current I of the cell is the difference of photo current I_L and diode current I_d.

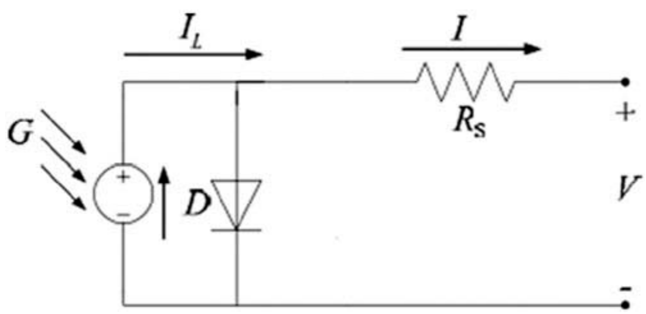


Figure 4. Circuit diagram of PV cell

$$I = I_L - I_o\left(e^{\frac{q(V+IR_S)}{nKT}} - 1\right) \tag{3}$$

where V = Cell voltage

T = Cell temperature

The temperature-dependent photocurrent I_L is

$$I_L = I_L(T_1) + K_o(T - T_1) \tag{4}$$

$$K_o = \frac{I_{SC}(T_2) - I_{SC}(T_1)}{(T_2 - T_1)} \tag{5}$$

where $I_L(T_1)$ is given in data sheet (measured under illumination of 1000 W/m^2)

T_1 is the reference temperature (25°C)

The diode saturation current I_o at the reference temperature is

$$I_o(T_1) = \frac{I_{SC}(T_1)}{\left(e^{\frac{qV_{oc}(T_1)}{nKT_1}} - 1\right)} \tag{6}$$

The diode saturation current at any other temperature is calculated by the following equation:

$$I_o = I_o(T_1) \times \left(\frac{T}{T_1}\right)^{\frac{3}{n}} e^{\frac{qV_g(T_1)}{nK\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \tag{7}$$

A typically I–V and P–V curve for a 500-W PV module, identifying V_{oc} and I_{sc}, and V_{mpp} and I_{mpp}, is shown in Figure 5. Power delivered is zero at the end of curve. At any other point on the I–V curve, PV module deliver certain power and that point is called operating point. The unique point occurs near the knee of I–V curve, where power is maximum, and that point is called MPP. The module produces the maximum power at MPP, as shown in Figure 5.

Perturb & Observer (P&O) method is used for MPPT. P&O method is most common and widely used algorithm for tracking the MPP of PV module (Anurag, Bal, Sourav, & Nanda, 2016). The flowchart of P&O is shown in Figure 6.

2.3. Modeling of pump

The centrifugal pumps are normally used for low-to-middle head applications. The power required by the pump is given as

Figure 5. *I–V* and *P–V* curve of a solar module

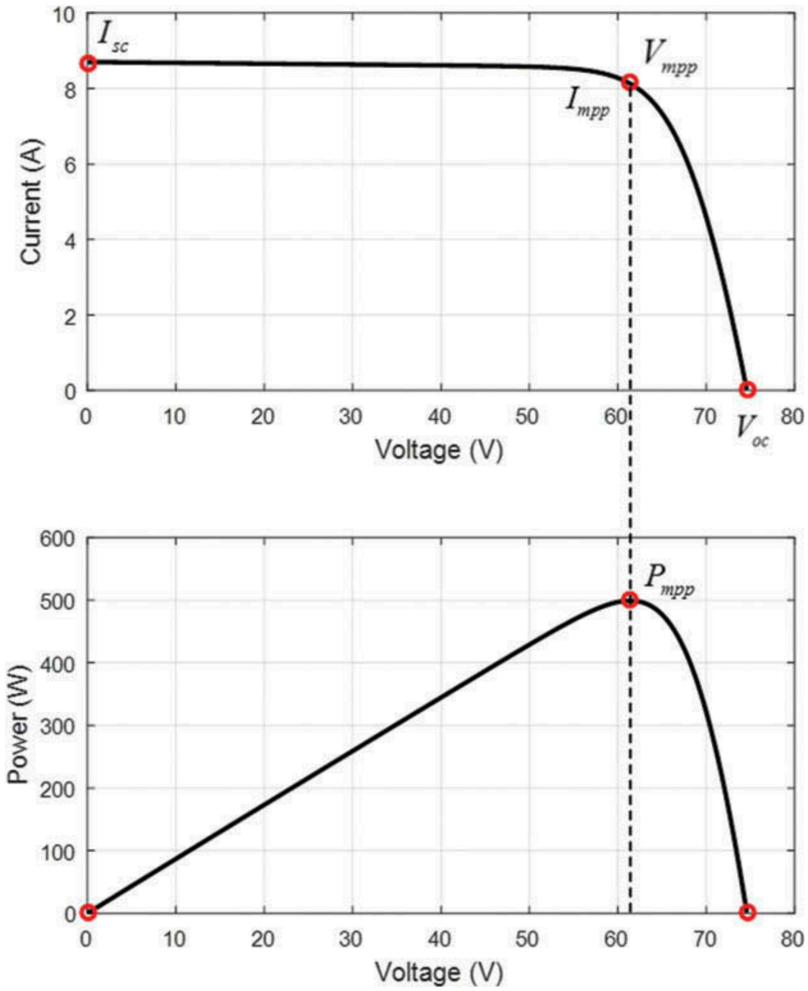
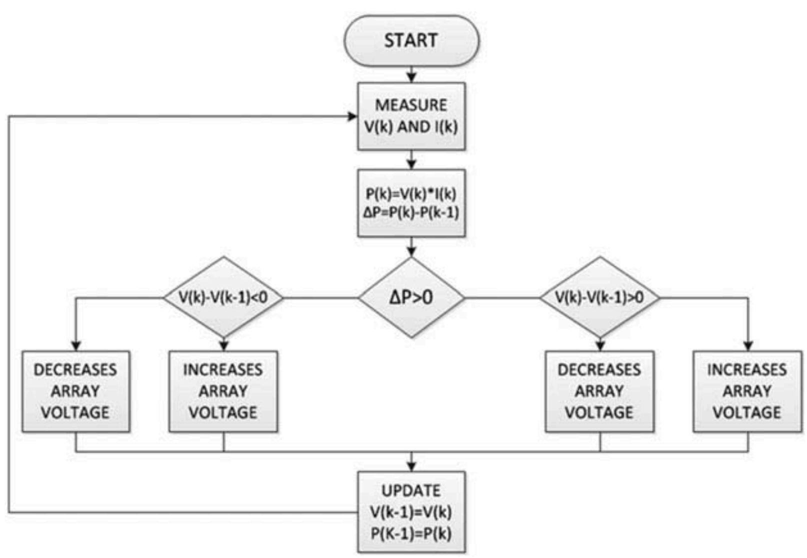


Figure 6. Flowchart of P&O algorithm



$$P_{in} = \frac{\rho \cdot g \cdot H \cdot Q}{\eta} \tag{8}$$

By applying the principle of motor-pump power balance equation (Khader & Daud, 2013), the above can be integrated with motor speed-torque performance as

$$\rho \cdot g \cdot H \cdot Q = \eta \cdot T_m \cdot \omega \tag{9}$$

The water flow rate can be written as

$$Q = \frac{\eta \cdot T_m \cdot \omega}{\rho \cdot g \cdot H} \ m^3/s \tag{10}$$

In this study, following pump parameters are selected:

$\rho = 1000 \ kg/m^3$

$g = 9.8 \ m/s^2$

$H = 20 \ m$

The speed of pump for a given flow rate is determined by centrifugal pump equation which is

$$H = aQ^2 + bQw + cw^2 \tag{11}$$

In this equation, a, b and c are constant which can be determined from pump geometry (Ghafouri, Khayatzadeh, & Khayatzadeh, 2012). For a given flow rate, the speed of the motor is determined, and the motor speed is regulated to desired speed to meet water demand.

3. Economic analysis

The economic analysis is very important to compare quantitative cost and benefit information. The goal of the economic analysis is to compare the proposed hybrid water pumping system with standalone PV powered water pumping systems. In economic analysis, life cycle cost (LCC), net present value (NPV) and the payback period are calculated. LCC is a key factor to be considered with the investment cost. It includes capital cost, maintenance cost, replacement costs and operational cost.

$$\text{LCC} = \text{CC} + \text{MC} + \text{FC} + \text{RC} - \text{SV} \tag{12}$$

where CC is the capital cost, MC is the maintenance cost, FC is the fuel cost, RC is the replacement cost, SV is the salvage value.

NPV shows the value of the entire system at the end of life cycle. It is the difference between the sum of discounted cash flows and initial invested amount.

$$\text{NPV} = \sum_{n}^{t} \frac{\text{Net period cash flow}}{(1+i)^n} - \text{Initial investment} \tag{13}$$

Payback period is the core part of the project. Payback period measures the time required to recover the investment cost. Shorter payback period is preferred and indicates the feasibility of the project.

A 10 hp (7.46 kW) motor is considered for pumping water from underground. The grid running cost is calculated according to current electricity tariff for agriculture in Pakistan. The operating hours are taken according to sun hours (8 h/day). In case 1, grid running system is replaced with standalone solar water pumping. The cost analysis is performed according to current market prices of all equipment including solar panels, pump, drilled bore, mounting structure, inverter, controller, installation, cabling, grounding etc. The solar panel operating life is taken 25 years. The capital cost

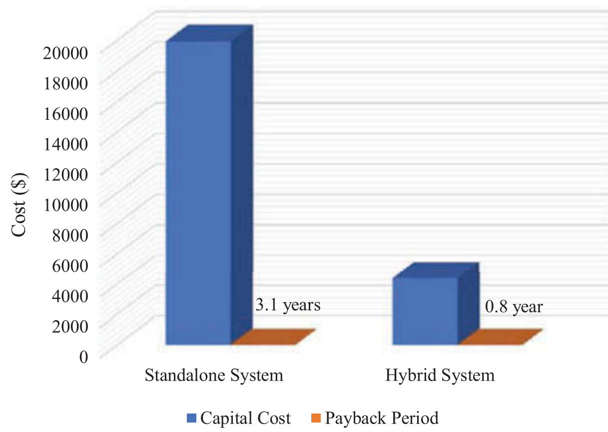


Figure 7. Cost analysis of standalone and the proposed hybrid water pumping system

of a 10-hp standalone solar powered system is $19,937, and the payback period is 3.1 years. In case 2, only a few solar panels are installed, instead of full solar deployment. The farmer can install more solar panels in future with the existing system thus decreasing initial investment. In this case, only 2 kW solar power capacity is installed and integrated with the existing grid powered system. In this case, the capital cost is $4380, and the payback period is 0.8 year. The capital cost and payback period are shown in Figure 7. The proposed system has much lower capital cost and the farmer can incrementally add more solar panels to the existing system in future, thus decreasing initial investment.

4. Design of controller for proposed system

In the proposed system, the input variable is flow rate Q [m^3/h]. The speed controller regulates the speed of the motor to the exact desired flow rate. If the utility is connected, the DC bus on the drive inverter remains stiff, the voltage is controlled by the utility and an increase in the flow rate demand is catered by increasing input power from the utility. In absence of utility power, the motor speed is limited by available input power from PV which depends on the size of panel and amount of insolation. In a typical scenario, without utility, the speed of the motor cannot be always regulated to meet the desired flow rate. In some case, where the load power is lower than PV potential, the PV panel is not operated at MPPT; instead, the control algorithm regulates DC bus voltage to 540 V by pulling down the duty cycle. If the load power is increased, the flyback converter output voltage starts to fall down below the set point, and MPPT control acts to regulate the voltage. The control structure for flyback converter is depicted in Figure 8.

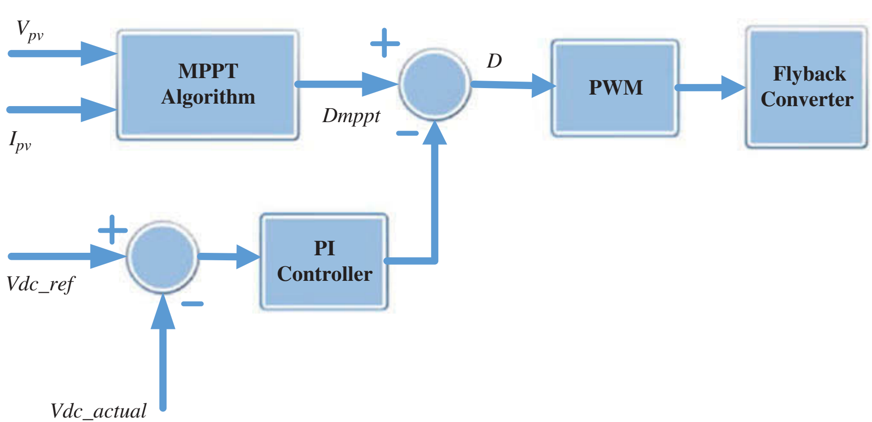


Figure 8. DC/DC converter control algorithm

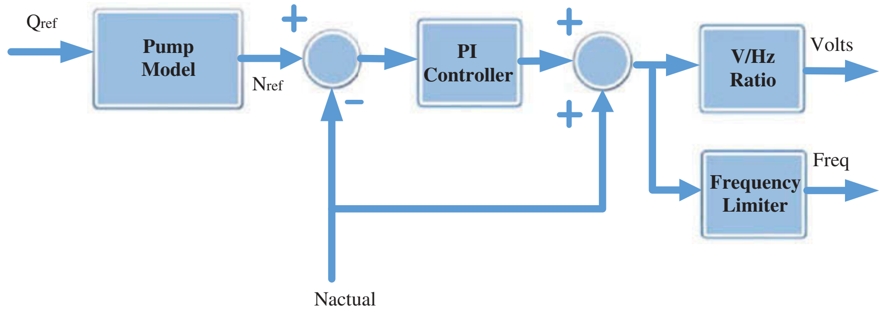


Figure 9. Motor speed controller

The motor speed controller is shown in Figure 9. The speed controller calculates the motor slip. The value of slip computed by the controller is added to the actual motor speed to produce the required inverter frequency. This frequency is also used to produce the required inverter voltage to maintain V/f ratio constant. Space vector pulse width modulation scheme is used to control the speed of the motor (Gajdusek, 2012).

5. Results and discussion

The proposed system is studied and analyzed in two cases under different flow rates.

5.1. Case I

In this case, a single PV panel with a nominal power of 500 W is used. The result of the complete system is displayed for various water flow rate and corresponding reference and actual speed. The speed of the motor is regulated according to water demand, which significantly reduces the power consumption. The flow rates are set [0.8 1.2 1.4 1 m^3/h] against time [0 1 2 3 s] respectively.

To meet desired flow rates, the power required from utility and solar power profile is shown in Figure 10. The motor mechanical speed, electromagnetic torque and DC bus voltage are shown in Figure 11.

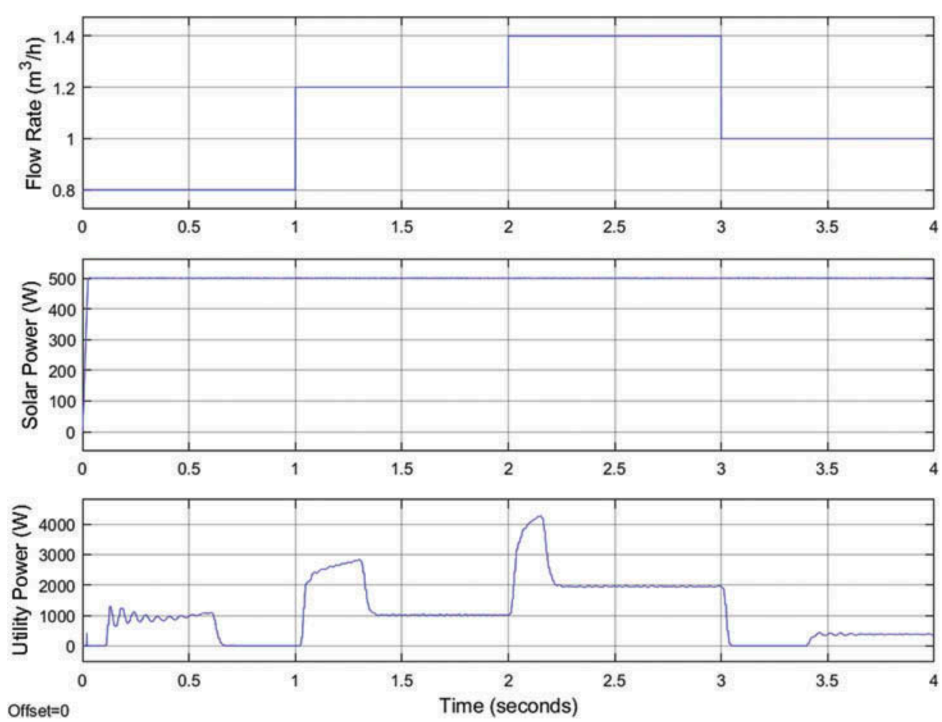


Figure 10. Power profile of PV panel and utility

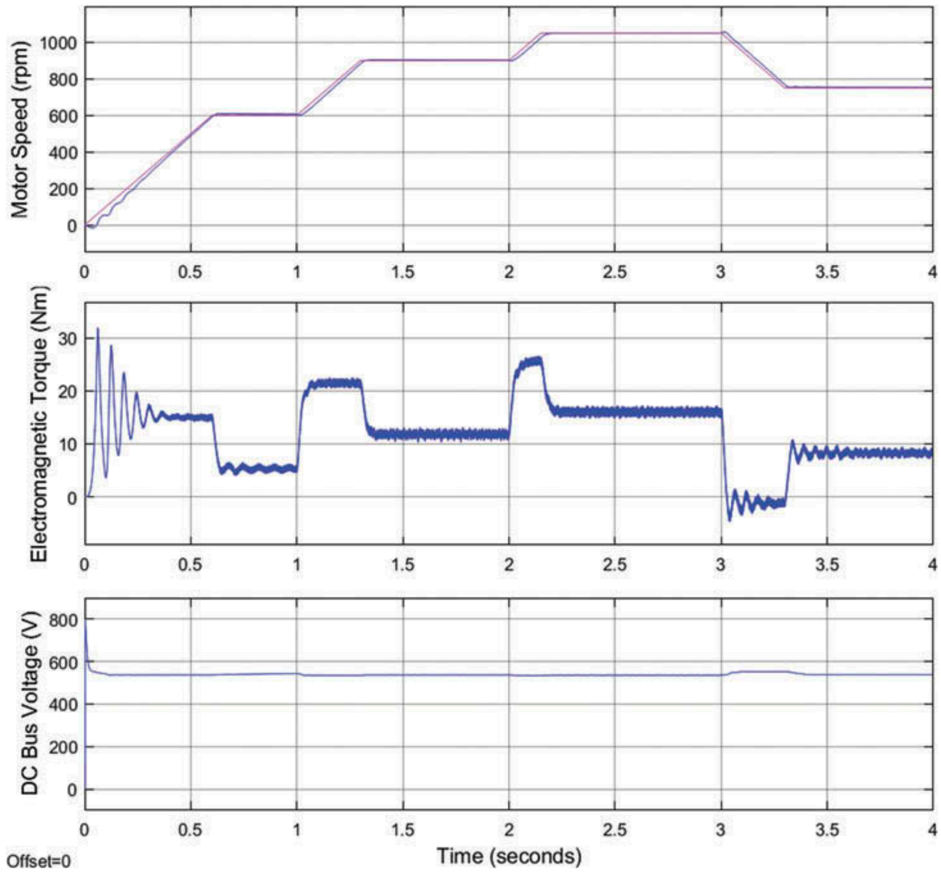


Figure 11. Motor speed, torque and DC bus voltage

The result shows that solar panel is operating at MPP and output power is 500 W. From the results, the motor is running from available solar power, and while taking remaining power from the utility. The 500-W power is coming from PV panel and remaining required power is added from the utility. The power demand depends on water flow rate. The system is mixing, both solar and utility power, to meet load power demand. The DC bus voltage increases, when the speed of the motor is decreased. This is because the mechanical power converted back into electrical, which charges the DC bus capacitor.

5.2. Case II

In this case, utility power is not available, which is common in rural areas. Two PV panels are used in this study in order to analyze the behavior of the proposed system. If utility power is not available, then for a given flow rate, the speed of the motor is regulated, while maintaining DC bus voltage at 540 V. If for a given flow rate the required output power is higher than available solar power, then DC bus voltage collapses. In this case, the motor speed is decreased to maintain DC bus voltage at set point. If solar power is more than the desired flow rate power requirement, then DC bus voltage increases. So, in such case, pump controller pulls down the duty cycle of MPPT, while maintaining DC bus voltage at set point.

The flow rates are set [0.6 0.8 1 0.8 m^3/h] against time [0 1 2 3.5 s] respectively. The power profile of solar panels is shown in Figure 12. The motor mechanical speed, electromagnetic torque and DC bus voltage are shown in Figure 13.

The results demonstrate that the controller is operating PV panels according to the desired flow rate. The PV panels are not operated at MPP when load power demand is low. When the load power demand is high, then pump controller operates PV panels at MPP, thus meeting the desired flow rate, while regulating DC bus voltage.

Figure 12. Solar panels power profile

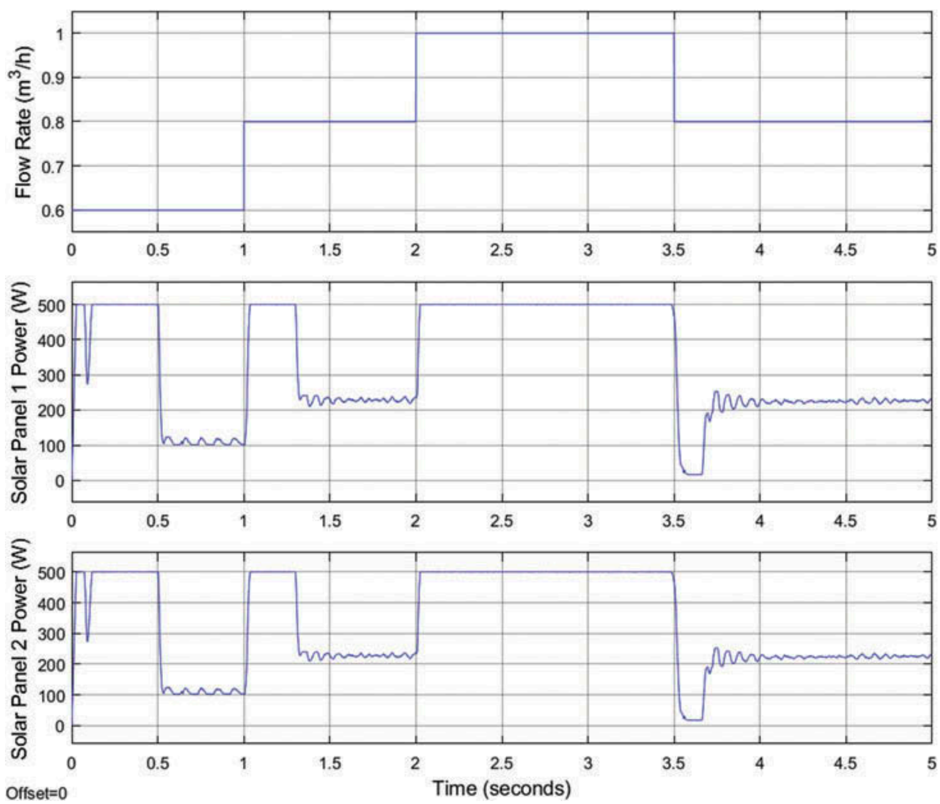
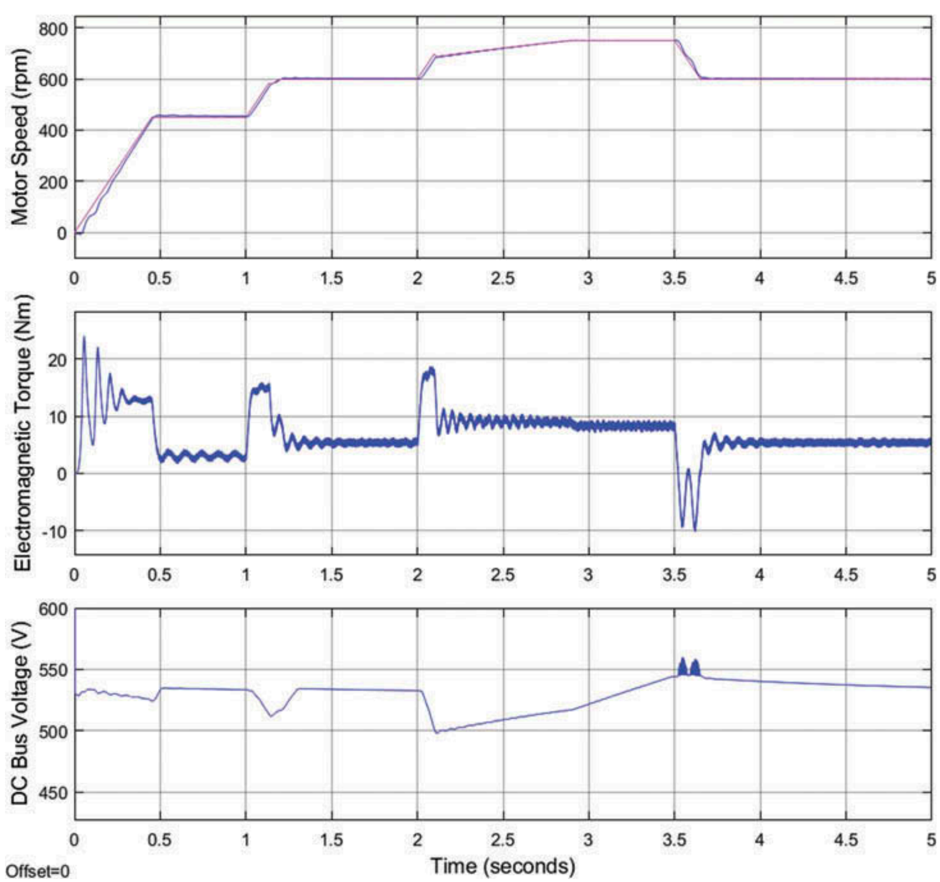


Figure 13. Motor speed, torque and DC bus voltage



6. Conclusions

This research has presented a novel arrangement for an irrigation pump, powered by both utility and solar panels. The MPPT is implemented using flyback converter to maximize solar energy harvesting. The power obtained from solar and utility are added at DC bus, which is used to drive three-phase AC induction motor. The results are presented to validate the operation of the proposed system. The advantage of this system is that the solution works with any number of installed panels, thus reducing initial investment, which is very high due to the cost of panels. The purpose of this research is to provide a reliable and cost-effective solution to the irrigation needs of the farmer in Pakistan. The farmer can incrementally add solar panels in future to the existing system, thereby reducing dependency on the utility power and electricity bills. This solution can lift farmers out of poverty by enabling them to better irrigate their crop more affordable, while decreasing their long-term energy costs, thus balancing economic development and environmental sustainability.

Nomenclature

PV:	Photovoltaic
DC:	Direct current
V_{OC}:	Open circuit voltage
I_{SC}:	Short circuit current
I–V:	Current–voltage
P–V:	Power–voltage
V:	Cell voltage
ΔV:	Ripple in the voltage
C:	Capacitance
f:	Frequency
Hz:	Hertz
A:	Ampere
W:	Watt
rpm:	Revolution per minute
I_O:	Diode reverse saturation current
R_S:	Series resistance
L_m:	Magnetizing inductance of flyback converter
G:	Irradiance (W/m^2)
n:	Diode quality factor
I_L:	Photocurrent
T:	Temperature (□)
K:	Boltzmann's constant (1.38065×10^{-23} J/K)
MPPT:	Maximum power point tracking
MPP:	Maximum power point
V_{mpp}:	PV module voltage at maximum power point
I_{mpp}:	PV module current at maximum power point
P&O:	Perturb & Observer
VSI:	Voltage source inverter
Q:	Flow rate
ρ:	Fluid density
g:	Gravity force

H:	Head of pump
η:	Efficiency
CC:	Capital cost
MC:	Maintenance cost
FC:	Fuel cost
RC:	Replacement cost
SV:	Salvage value
LCC:	Life cycle cost
NPV:	Net present value
i:	Interest rate
D:	Duty cycle

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