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Research article

Toward improving water-energy-food nexus through dynamic energy management of solar powered automated irrigation system

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A R T I C L E I N F O

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A B S T R A C T

This paper focuses on developing a water and energy-saving reliable irrigation system using state-of-the-art computing, communication, and optimal energy management framework. The framework integrates real-time soil moisture and weather forecasting information to decide the time of irrigation and quantity of water required for potato crops, which is made available to the users across a region through the cloud-based irrigation decision support system. This is accomplished through various modules such as data acquisition, soil moisture forecasting, smart irrigation scheduling, and energy management scheme. The main emphasizes is on the electrical segment which demonstrates an energy management scheme for PV-battery based grid-connected system to operate the irrigation system valves and water pump. The proposed scheme is verified through simulation and dSpace-based real-time experiment studies. Overall, the proposed energy management system demonstrates an improvement in the optimal onsite solar power generation and storage capacity to power the solar pump which save the electrical energy as well as the water in order to establish an improved solar-irrigation system. Finally, the proposed system achieved water and energy savings of around 9.24 % for potato crop with full irrigation enhancing the Water-Energy-Food Nexus at field scale.

1. Introduction

Increasing population across the globe demands more food production. However, the changing climate causes declining water availability and thus leading to the water and energy shortages across all the sectors including mainly the agriculture [1]. To maintain the current per capita supply, the food production needs to be increased by around 50 % in the next 50 years to feed the rising population, which further intensifies the demand for water and energy [2]. In this scenario, any poor agricultural practices will further intensify the negative effects, leading to more vulnerable situations. While the accessibility to surface water resources is limited, groundwater contribution is a major source of irrigation. Nearly two-third (64 %) of irrigated agriculture in India depends on

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groundwater sources, which is depleting at an alarming rate due to inefficient irrigation management and unreliable power supply [3]. Consequently, about 30 % of the aquifers are in a critical state, threatening the sustainability of groundwater utilization [4]. The urgency of this water-energy nexus investigation stems from the shortage of water and energy, a phenomenon that is intensifying recently both in India and across the world. Irrigation efficiency has direct implications on the nexus between water usage and power consumption. According to the organization for economic co-operation and development's environmental outlook 2050, Indian agriculture would face severe water constraints/shortages in the next thirty years [5]. Supplying precise amount of irrigation water (i.e., right quantity at the right time) not only saves water used for irrigation but also protects the groundwater resources and further reduces power consumption used for pumping. For this endeavor, solar water pumps could be a viable alternative for both optimal irrigation and energy from the utility grid [6].

Irrigation scheduling can be categorized into plant-based-, soil moisture based-, and weather-based approach [7]. In the existing literature most of the automatic irrigation and monitoring systems are typically based on soil moisture approach, often integrated with weather parameters (e.g. rainfall) [8]. There are a variety of water-saving techniques for diverse crops, ranging from the most basic to the most technologically advanced. Notably, a remote canopy temperature-based approach employed infrared thermometers to automate the cotton crop irrigation, the automatic irrigation system activated by canopy temperature threshold [9]. Similarly, implementing an evapotranspiration (ET) based automatic irrigation scheduling system to compute the crop irrigation requirement and time of water application achieved up to 42 % water saving [10]. Innovative strategies, such as soil sensors and evaporimeters are used to further reduce/adjust the irrigation based on the daily weather or substrate moisture content fluctuations [11]. Advancements in wireless sensor networks (WSN) have facilitated irrigation machinery control. Multiple studies have explored WSNs to monitor various parameters such as soil moisture, temperature, humidity, and illumination to maintain optimal conditions for crop growth [12, 13]. A novel irrigation scheduling system was developed in Ref. [14] to plan for more accurate water allocation using earth observation data, weather forecasts, and numerical simulations. To overcoming the challenges in WSN systems, recent advancements in micro-electronics and wireless technologies generated low-cost, low-power components, power-aware protocols, task management, and communication solutions [15,13] are useful.

Since the groundwater based irrigated agriculture contributes major share of total agricultural products, approximately 31.8 million pumps have been installed, which are being operated by grid power and diesel engines [16]. Recently, the solar powered water pumping systems have gained significant attention [17,18], which can be off-grid or grid connected. The solar based pumping mainly helps in effective utilization of grid power, effective use of sensors, to achieve high efficiency in the power electronic conversion modules, and thus to reduce the loading on utility grid. Several research papers have discussed the performance improvement of solar pumps in terms of battery storage [19], environmental impact assessment [20], comparison of DC and AC motors [21], comparing the pumps such as centrifugal, submersible and displacement pumps [22]. Further, solar water pumping system with water storage tank was introduced to address the reliability and life cycle cost issues [23].

Based on the literature review presented, it was noted that the integration of both water and energy management still needs further improvements especially at field scale. Therefore, the paper proposes an energy management scheme to maximize the utilization of photovoltaic (PV) capacity and ensure the power supply security during overcast conditions. The goal of the study is to demonstrate that automated irrigation system reduces water and power consumption for enhancing the Water-Energy-Food nexus at field scale. This was achieved adopting the following tasks a) to develop wireless sensor network (WSN) nodes to measure soil moisture and local weather and cloud-based irrigation decision support system using the Internet of Things (IoT), b) to develop an onsite optimal energy

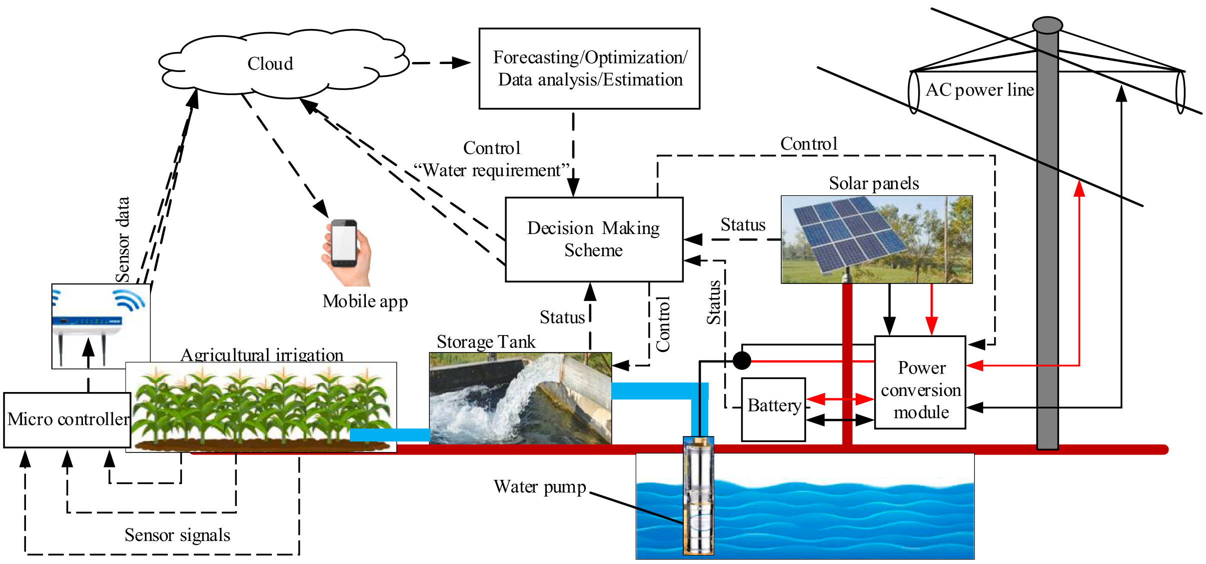

Fig. 1. Water and energy-efficient reliable irrigation system (WatEr-ERIS).

management strategy to operate the solar-powered automated irrigation system, c) to implement a well-structured integration of all the sources and loads (pump), d) to demonstrate the interconnected system for irrigation experimentally, and e) to apply the energy management and control systems for improving irrigation in more economical and energy-efficient way. Fig. 1 illustrates the overall integration of the water and energy-efficient reliable irrigation system (WatEr-ERIS).

The WatEr-ERIS encompasses an array of modules which are explained in detail in the subsequent sections. The main focus of this paper includes:

- A rule-based energy management and control schemes for a grid connected solar water pumping system for water and energy-efficient reliable irrigation system.
- The seamless operation of the Interior Permanent Magnet Synchronous Motor (IPMSM) drive is reported with Battery, PV on grid-connected mode or island mode based on energy management scheme.
- A Maximum Power Point Tracking (MPPT) operation for PV is achieved along with the DC-link voltage regulation.
- The abnormal condition of grid performance is also analyzed with voltage sag and swell scenarios.

The paper is arranged in the following manner. The realization of the proposed work is given in Section 2. Section 3 elaborates various modules to achieve automated irrigation system. The proposed energy management scheme is explained in Section 4. The discussion over experimental results is made in Section 5. Finally, Section 6 summarizes the paper.

2. Realization of proposed system

The proposed study focuses on the rural areas (Kataula, Salgi etc.) of Mandi District, Himachal Pradesh, India, where significant water shortage is affecting mainly groundwater irrigation. The open-source satellite products are updated on a daily basis, and field observed meteorological parameters are used to forecast the local weather for 5–7 days lead period and store it in the cloud [24]. The soil moisture and temperature sensors along with Internet of Things (IoT) devices, are used to transmit the data to the cloud. The cloud provides crop-specific irrigation information to the users along with other weather parameters such as rainfall, solar irradiation, temperature, and soil moisture level. The pump can be operated through mobile apps to irrigate, irrespective of power supply from the grid is available or not. During the power shutdown, pumps are operated from the onsite power backups, which are recharged by the solar PV system.

The integration of all the entities such as PMSM drive, PV, and energy storage system are achieved with help of power electronics converters. Based on the power conversion stage, converters can be classified as single-stage and two-stage topologies. In power electronics, there exist a major challenge to establish a regulation of desired voltage or current and hence the configuration must be chosen carefully. For this purpose, a two-stage power electronics topology typically consisting of two converters in the overall power

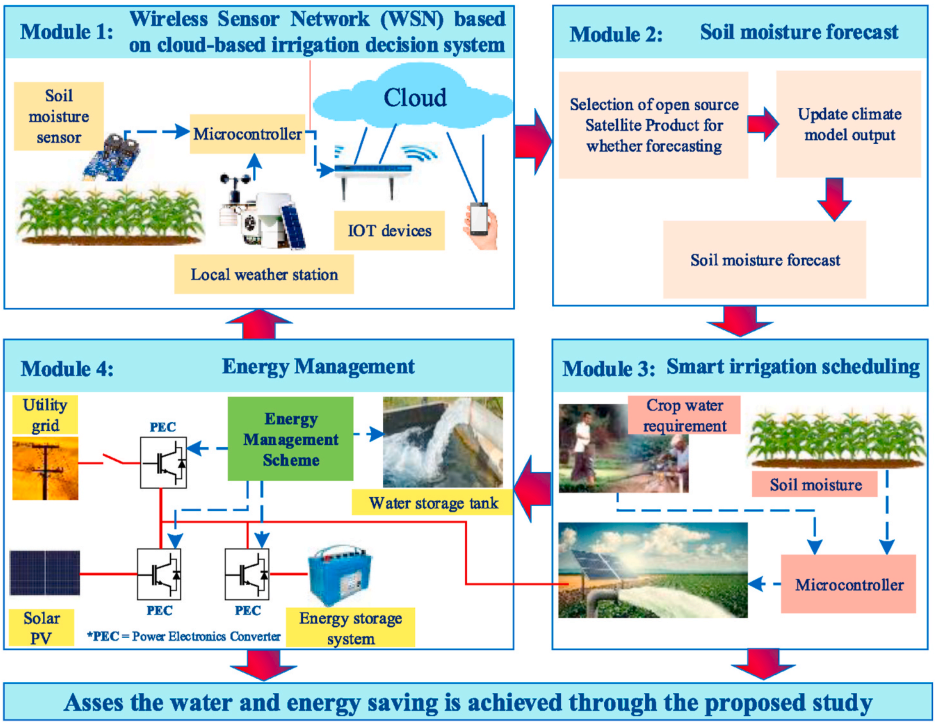

Fig. 2. WatEr-ERIS flow with various modules linkages.

conversion process is chosen. The key advantage of the two-stage topology is that it requires the small capacitance size for strict voltage regulation and achieving in better maximum power point tracking capability.

In a two-stage topology, the voltage regulation is excellent as compared to the single-stage converter topology. Several converters are used to accomplish the objective. A front-end DC-DC boost converter is interfaced between the PV panel and DC link. For PV application, two-stage configuration also provides the MPPT efficiency and system dependability. Another DC-DC bi-directional converter is connected to battery. In combined, both circuitry makes it a two-stage DC-DC converter. Here, first DC-DC converter is used for extracting maximum power and the second converter is used for maintaining the constant DC link voltage [25–27]. To extract the maximum power from the PV, the perturb and observation (P&O) algorithm is used. Another, two-stage configuration is used for interconnection of PMSM drive and the AC grid. In this, front-end single phase voltage source inverter (VSC) connects AC grid to the common DC link. Whereas another three phase VSC is used to connect PMSM drive with DC link. In order to control the speed of the PMSM, a hysteresis current controller is used. The performance is analyzed with different operating conditions such as motoring and regenerative braking condition. The more details about the power stage of the converters are elaborated in section 5 which is an experimental part of this study.

3. Automated irrigation system

WatEr-ERIS framework consisting of various modules is shown in Fig. 2. The framework is divided into four modules based on their assigned task and the details about each module has been comprehensively discussed below.

3.1. Module 1: development of WSN

Automatic soil moisture and weather station as shown in Fig. 3(a) feed the data for soil moisture forecasting to Module 2. IoT-based sensor is used to send the data to the LoRa-gateway. Sensors send the data at every 1-h interval. LoRa-gateway is connected to the network, and it sends the data to the personal computer (PC) for forecasting the soil moisture value using the framework published in Ref. [28]. A weather station is installed on the campus, connected to the LoRa gateway, sends the weather satellite data. A drip irrigation system as shown in Fig. 3(b), has been installed in the field at IIT Mandi for conducting the field experiments (it is almost one km away from the agriculture field).

3.2. Module 2: short-range soil moisture forecasting

Module 1 provides the information of the soil moisture and weather information measured at the field. In Module 2, a machine learning based long short-term memory (LSTM) model was developed to forecast the soil moisture (SM). LSTM is a robust model in forecasting the sequential timeseries information by accounting vanishing gradient problem. For scheduling the irrigation, 5 days ahead prediction of the soil moisture content is required. Accordingly, the SM was forecasted for up to 5 days ahead including the 1 and 3 days ahead forecasting.

The input variables for the LSTM model consists of meteorological parameters such as rainfall [P] (mm), temperature [T] (^{o}C), relative humidity [H] (%), wind speed [W] (kmph), dew point [D] (^{o}C) along with soil moisture measured using field sensors. The summary statistics of selected input variables for modelling is presented in Table 1. Based on the cross, and auto correlation the most significant inputs were identified correspondingly to current time (t) and different lagged time (up to t-2). The final input model structure was fixed and the outputs are the soil moisture corresponding to the required forecast lead (t+1, t+3 and t+5).

Fig. 4 illustrates the correlation between different input variables also with output (soil moisture at time 't'). It is clear that despite different levels of correlation estimated among the input variables, the overall correlation with output variable varied between −0.125 and 0.2907. Unlike other hydrological variables such as surface runoff, evapotranspiration, the correlation was not very strong in the case of soil moisture corresponds to weather parameters. However, the influence of weather parameters on the soil moisture cannot be

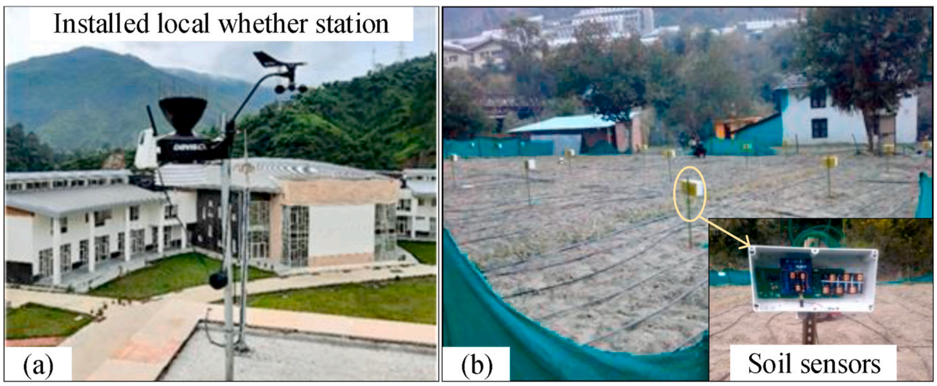

Fig. 3. Realization and acquisition of soil moisture measurement.

Table 1
Summary statistics of the input data variables for forecasting model for the period December 4, 2021 to April 30, 2022.

Statistical Index	Temperature (°C)	Relative Humidity (%)	Rainfall (mm)	Wind Speed (kmph)	Dew Point (°C)	Soil Moisture (m^3/m^3)
Mean	13.00	62.67	14.29	2.99	4.54	0.20
Standard deviation	5.31	15.48	39.72	1.87	3.03	0.04
Skewness	0.49	−0.19	3.22	1.95	0.18	0.18
Minimum	6.22	32.29	0.00	0.67	−3.95	0.15
25th Percentile	8.26	47.58	0.00	1.68	2.39	0.16
75th Percentile	17.74	72.73	1.40	3.84	7.19	0.23
Maximum	23.90	96.42	197.60	12.21	11.60	0.29

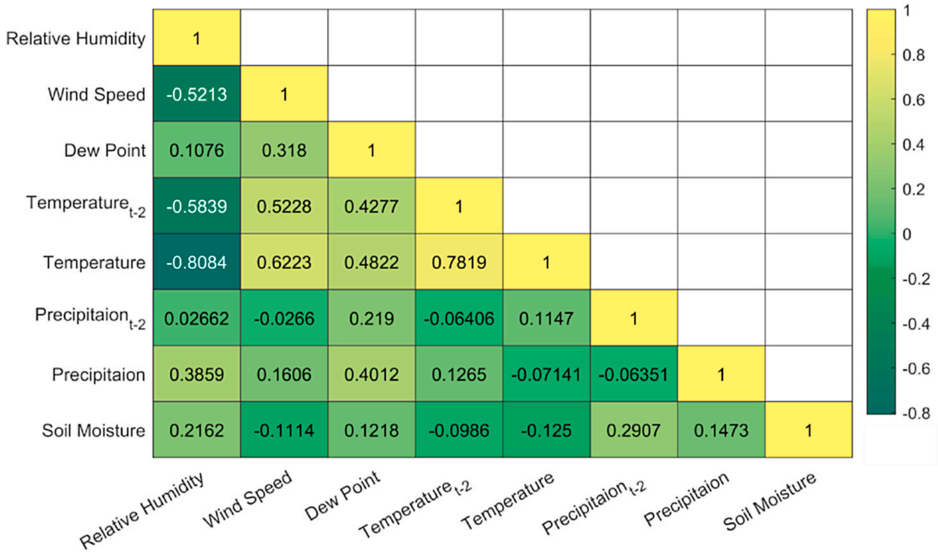

Fig. 4. Correlation matrix plot of input and output variables.

ignored so as to allow the LSTM model to train with diverse sets of inputs capturing the underlying physics of the system.

The model is constructed using single layer LSTM cells with 32 units connected to 4 layers of fully connected neural networks. The LSTM model is optimized using Adaptive Moment Estimation (ADAM) with mean squared error as the loss function. The model is trained and tested to forecast SM 5-days ahead (SM_{t+5}). To achieve better accuracy, the 5-days ahead rainfall forecast collected from block level India Meteorological Department forecast was used.

The observed hourly data of the weather information and soil moisture from December 2021 to April 2022 was used to develop the SM forecast module. The model was trained optimizing the 5697 parameters (weights and biases) with the hyperparameters learning rate, 0.001 and batch size of 32. The model performance was assessed using Nash Sutcliffe Efficiency index (NSE) for 1-day, 3-day and 5-day ahead forecast. Overall a good fit between observed and forecasted was found and the NSE estimated are presented in Table 2. As the dynamics of SM was very consistent, the model performance was almost similar across all the lead time. Furthermore, the ability of LSTM learning sequentially the underline trend of the data allows the model performance not to deteriorating even the lead time increases. The testing period results of 5 days ahead SM forecast is illustrated in Fig. 5. The results of 1- and 3- days ahead forecast are not presented herein for brevity. Further, it is confirmed from Table 3 that the statistical estimates (mean, standard deviation and skewness) of observed and forecasted soil moisture closely matches with each other across all the lead time (1- day, 3-day and 5-day).

3.3. Module 3: smart irrigation scheduling

All the data received from Module 2 helps calculate the actual crop water requirement (CWR). In this study, the CROPWAT 8.0 simulation platform has been used to calculate the net CWR. The CROPWAT 8.0 utilizes weather data including rainfall, temperature,

Table 2
Performance of the LSTM in forecasting soil moisture.

Forecast	NSE (Training)	NSE (Testing)
1 Day Forecast	0.948	0.948
3 Day Forecast	0.948	0.933
5 Day Forecast	0.946	0.937

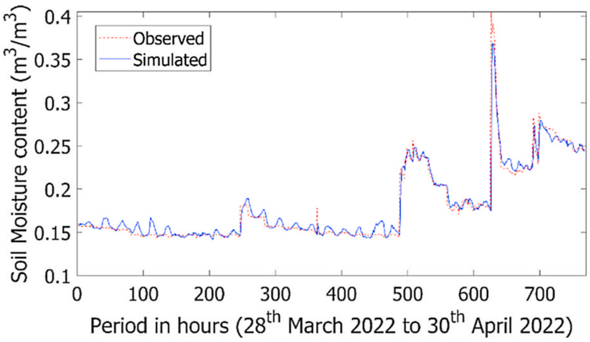

Fig. 5. Soil moisture forecast by LSTM network for 5 days ahead during testing period.

Table 3
Summary statistics of the forecasted soil moisture.

Statistical Index	1-Day		3-Day		5-Day	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
Mean (m^3/m^3)	0.178	0.178	0.179	0.181	0.180	0.181
Standard Deviation (m^3/m^3)	0.043	0.040	0.044	0.040	0.045	0.042
Skewness	1.785	1.569	1.711	1.496	1.616	1.340

relative humidity, and wind speed, crop data, and soil data in order to evaluate CWR [29]. Here, weather data is taken from the automatic weather station installed near the experimental field. According to crop water requirements, the decision support scheme turns ON/OFF the motor. The process to check the status of water requirement is given in Fig. 6. The amount of net irrigation required by the crop is a very important aspect. To achieve this Module 3 processes and computes the net irrigation. The computed irrigation required, and the water supplied by the pump and reservoir together are represented as D (liters/hectare) and S (liters/hectare), respectively in Fig. 6. The net irrigation depends on various parameters such as field capacity, the water level of the reservoir, rainfall status, etc.

The soil present in the experimental field is silty loam with field capacity (FC) of 32 % and wilting point of 12 % (available water 20 %). Field capacity is defined as water retained in the field due to molecular attraction and by loose chemical bonds after irrigation or rain. The FC can be expresses as eq. (1). Allowable depletion is 80 % of available water (i.e. irrigation water is applied when the soil moisture goes below 16 % to bring back to 32 %). The effective root zone depth is measured as 47 cm. The depth of water (d) stored in the root zone is calculated using eq. (2) [30] and is comes out to be 11.3 cm.

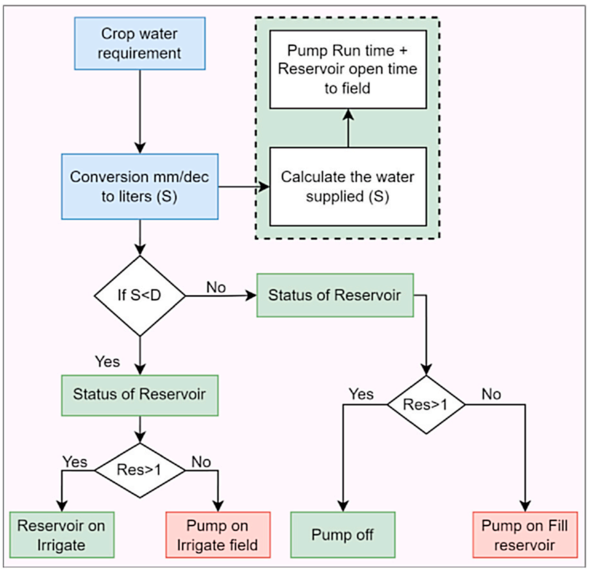

Fig. 6. Flowchart for the status of water requirement [D indicates water supplied by pump and reservoir together in liters/hectare].

Field capacity (FC) = Volume of water retained in the soil after initial drainage by gravity / Volume of soil. (1)

$$d=\frac{\Upsilon_d}{\Upsilon_w}d\ (FC\ -\ \text{allowable depletion of available water}) \tag{2}$$

where, Υ_d and Υ_w are the density of dry soil and water, respectively. The values of Υ_d and Υ_w taken from the field are 14.78 KN/m^3 and 9.81 KN/m^3, respectively.

Considering the irrigation efficiency of 80 %, volume of water stored in the root zone is 33.9 m^3 (field size is 20 m × 15 m) and volume of water pumped/supplied from the source is 42.375 m^3. The data for decadal crop water requirement for potato, effective rainfall, soil water availability are presented in Table 4. It can be noticed that for crop periods, November to March, two-time irrigation is required. Therefore, total volume of water supplied for the experimental field is 84.75 m^3 (equivalent to 2825 m^3/ha). However, conventional irrigation requirement is calculated as 3086.25 m^3/ha based on the flood irrigation method and potential evapotranspiration requirement of the crop for the field location [31]. Here, water saving achieved is around 261.25 m^3/ha (9.24 %) under no water stress condition. With pump discharge rate of 0.03 m^3/Sec, the total time to run the pump is calculated as 84.75/0.03 = 2825 Sec or 0.78 h. At last, the total energy consumed is computed in eq. (3)

Total energy Consumed = 3.7 kW × 0.78/0.9 = 3.2 kWh (3)

For 1 ha, the soil moisture-based irrigation requires around 26.15 h of pumping which consume about 96.80 kWh of energy, whereas conventional irrigation requires around 28.57 h of pumping which consume 105.7 kWh of energy. Compared conventional irrigation, soil moisture-based irrigation saved around 8.9 kWh.

3.4. Module 4: energy management scheme

The energy management scheme (EMS) is initiated with reference to the inputs received from the forecasting and crop simulation models, which deal with soil moisture forecasting, growth prediction, genetic features of specific cultivar, environmental variables and management practices etc. If solar powered automated irrigation system is not adequately managed and operated, it may lead to wasteful energy and water use. Hence, an EMS is proposed and a detailed discussion is presented in the next section.

4. Proposed energy management scheme

Irrigation can be improved in a more cost-effective and energy-efficient manner with well-implemented energy management and control systems. Therefore, this paper proposes a rule-based energy management and control schemes for a grid connected solar water pumping system. The EMS is initiated with reference to the inputs received from the forecasting and crop simulation models, which deal with soil moisture forecasting, growth prediction, genetic features of specific cultivar, environmental variables and management practices etc. The EMS requires the prior knowledge regarding operational status of various entities such as availability of PV power, water level in storage tank, state of charge of storage battery and availability of grid by means of placing suitable sensors. Estimation of State of Charge (SoC) of battery is an important parameter and the estimated SoC decides the operational states of the energy management scheme. Finally based on objective function defined, EMS generates the reference variables for controllers, that control the power electronic interfacing devices. Whole data is transferred to cloud through IoT, which is retrieved by other modules and monitored.

To achieve this objective, the proposed EMS is implemented on the system shown in Fig. 7. The flowchart of proposed EMS is shown in Fig. 8. This figure also illustrates various control strategy for different converters. The operation is carried out in such a way where, PV side DC-DC boost converter operates in the MPPT mode derived using P&O algorithm. The proposed system operates in two modes i.e., grid-connected mode and island mode. The working modes of the converters are chosen in accordance with the EMS, as indicated in Fig. 8. This EMS leads to the definition of distinct cases, which are then carried out and confirmed through experimental tests. In the

Table 4
Irrigation Assessment for Potato based on Water Consumption.

Date	Crop Water requirement (mm)	Rainfall (mm)	Water Available (mm) (Initial = 113)	Irrigation required
Nov 21, 2021–Nov 30, 2022	4.8	1	113–4.8 + 1 = 109.2	Y
Dec 1, 2021–Dec 10, 2021	10.6	1.2	109.2–10.6 + 1.2 = 99.8	N
Dec 11, 2021–Dec 20, 2021	9.4	0	99.8–9.4 + 0 = 90.4	N
Dec 21, 2021–Dec 31, 2021	11.2	0	90.4–11.2 + 0 = 79.2	N
Jan 1, 2022–Jan 10, 2022	11.1	0	79.2–11.6 + 0 = 67.6	N
Jan 11, 2022–Jan 20, 2022	11.6	0	67.6–11.6 + 0 = 56	N
Jan 21, 2022–Jan 31, 2022	14.4	0.1	56–14.4 + 0.1 = 41.7	N
Feb 1, 2022–Feb 10, 2022	14.4	0.7	41.7–14.4 + 0.7 = 28	N
Feb 10, 2022–Feb 20, 2022	15.6	1.1	28–5.6 + 1.1 = 13.6	N
Feb 21, 2022–Feb 28, 2022	14	0.8	13.6–14 + 0.8 = 0	Y
Mar 1, 2022–Mar 10, 2022	2	0	113-2+0 = 111	N

*Y = Yes and N==No.

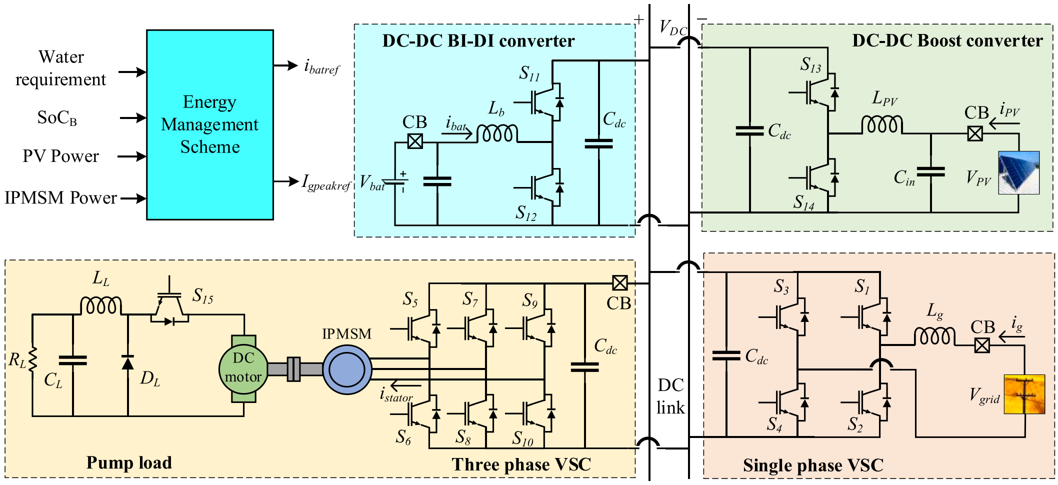

Fig. 7. The system architecture of proposed system contains converters and pump load.

following section, these studies are well-explained.

When the AC grid is OFF, battery side BI-DI DC-DC converter regulates the DC-link voltage. If the irrigation is not required i.e., IPMSM pump drive is OFF, the PV power injects into the battery completely. Therefore, the battery begins to charge up to its maximum capacity. As the battery is fully charged, the PV feeds the power into the grid. Once the sun is not available, then the battery provides the energy to the IPMSM drive pump. If the SOC of battery (SOC_B) is less than 10 %, then grid feeds power to the pump. The grid assumes control of the DC link voltage as soon as it is connected and regulates it to the required value. In this instance, the system contains both a PV and an AC grid, and the PV supplies electricity to the AC grid.

The whole process ensures the maintenance of power flow. So that maximum power of PV is utilized completely. The pump operates in its optimal condition. According to water requirements, the motor operates at different speeds. Here, a dual loop control (inner current loop and outer voltage loop) is used. When PV current (i_{PV}) is more than the required current, the DC-link voltage (V_{DC}) is greater than the reference voltage (V_{ref}), and both the voltages are compared, and error is fed to the PI controller. At this time, the outer voltage controller generates the negative reference current. The actual battery current (I_b) is compared to the generated reference current (I_{bref}), and again, error is fed to the PI controller that generates the pulses for the respective switches. Another PI controller is used for control the speed of IPMSM. Fig. 8 illustrates the control strategies on the individual converters.

5. Experimental study

The experimental prototype of the grid integrated solar PV array and battery fed IPMSM drive is developed in the laboratory as in Fig. 9. Here, the IPMSM motor emulates a water pumping system for irrigation. In the power stage, a PV, battery, and AC grid utility are used as active sources and IPMSM motor is used as pump load. The 3.7 kW IPMSM (JD engineering works) is coupled with the DC machine and connected to DC link through IGBT based VSC (Semikron converters). To emulate solar PV, a TerraSAS photovoltaic simulator (EGAR) is utilized. In the control unit, a digital controller dSPACE-1104 is used to operate the system in real-time. To acquire the voltage and current data, the hall effect voltage and the current sensors are used, respectively. The parameters selected for experimental study are given in Table 5. The different cases have been studied which are as follows.

5.1. Case 1: PV with battery

The performance is tested at different solar irradiance. At 1200 W/m^2 and 200 W/m^2 (at 25 °C constant temperature), the PV current and voltage are the 3.9 A and 110 V, and 0.4 A and 102 V, respectively. In this case, the pump load is not connected hence, the PV feeds the power to the battery. The tracking efficiency of MPPT achieved is 98 %–99 %. The experimental results for this case are shown in Fig. 10. It can be observed that at t_1, t_2, t_3, and t_4, when solar irradiance decreases, the power is delivered to battery is also decreases. But the DC-link voltage (V_{DC}) remains regulated.

5.2. Case 2: PV with AC grid utility

This case occurs when the battery is charged completely then the PV power is transferred to the AC grid utility. At this time, the grid maintains the V_{DC}. Since the reference is zero before the grid is ON, PV current i_{PV} begin to increase, hence, the grid reference current I_{gref} also increases to maintain the constant DC-link voltage. Fig. 11 illustrates the results for this case. In Fig. 11(a), it can be seen that at t_5, as the solar irradiance change from 800 W/m^2 to 1200 W/m^2, the i_{PV} also increases from 3.2 A to 4.8 A. Hence, the i_g also increases up to some level. Similarly, the effect of i_{PV} and i_g under decrement in solar irradiance form 1200 W/m^2 to 800 W/m^2 at t_6 is shown in

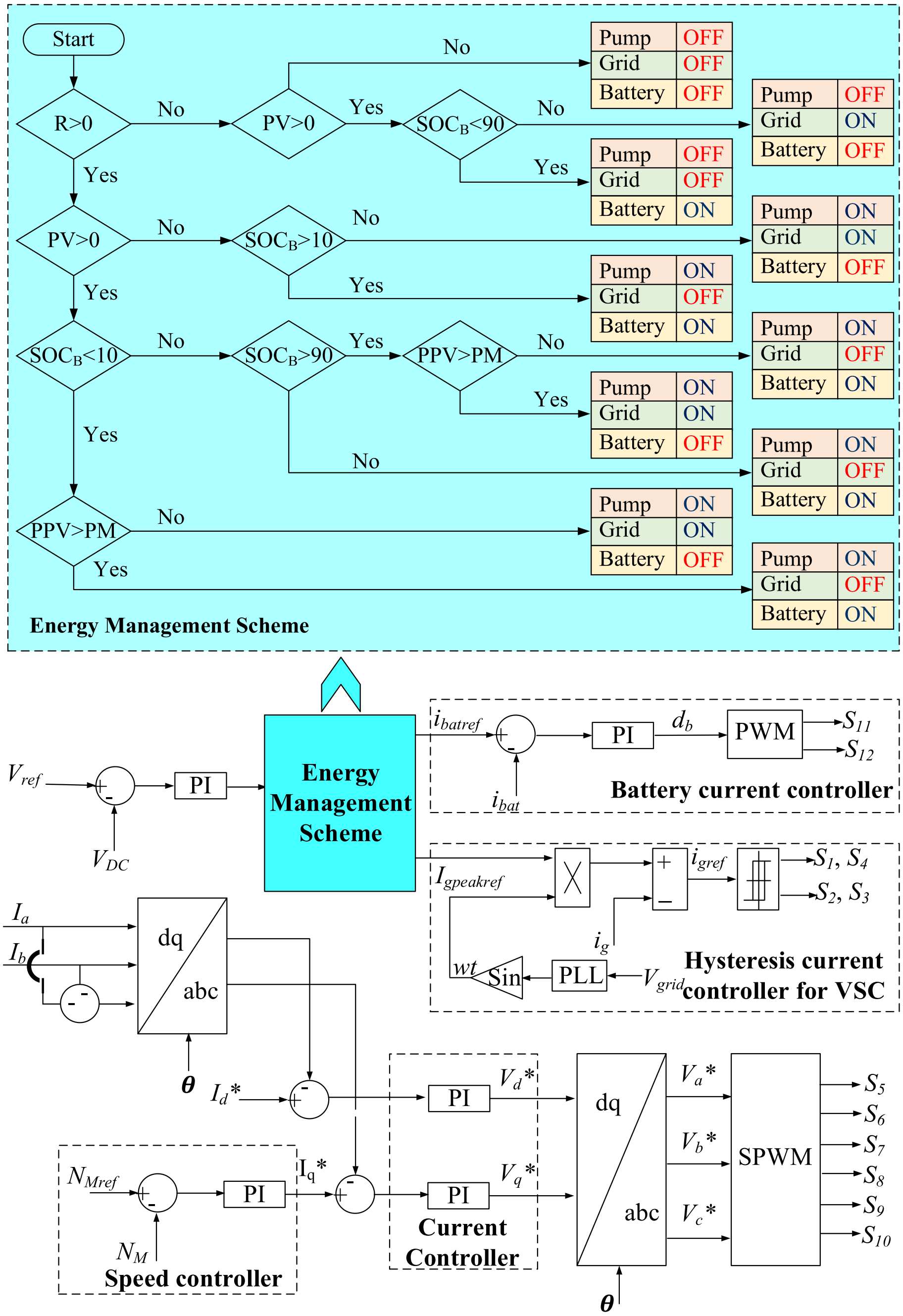

Fig. 8. Proposed Energy Management Scheme along with control strategies for different converters.

Fig. 11(b). The transients during turning ON of PV while grid is ON can be seen in Fig. 12. Here, the PV (solar irradiance: 1000 W/m^2) is turned ON at t_7 and delivers the power to the AC grid. In this mode, the i_g is out of phase from V_g.

5.3. *Case 3: pump load with AC grid*

This case represents a scenario when solar power is not available (i.e., PV is OFF), the battery is fully discharged and the pump (IPMSM) requires the power to run. At this time the AC grid feed the power to the IPMSM. The transient and steady-state behavior of IPMSM is shown in Fig. 13. At t_8, IMPSM gets turned ON and start to run and then settle at 400 RPM. The peak value of grid current (i_g) and motor stator phase current (i_{stator}) are 2 A and 2.5 A, respectively.

The AC grid performance is observed at $V_g = 120$ V (RMS). At t_9, the speed has been changed to 1000 RPM. During this time, i_g and

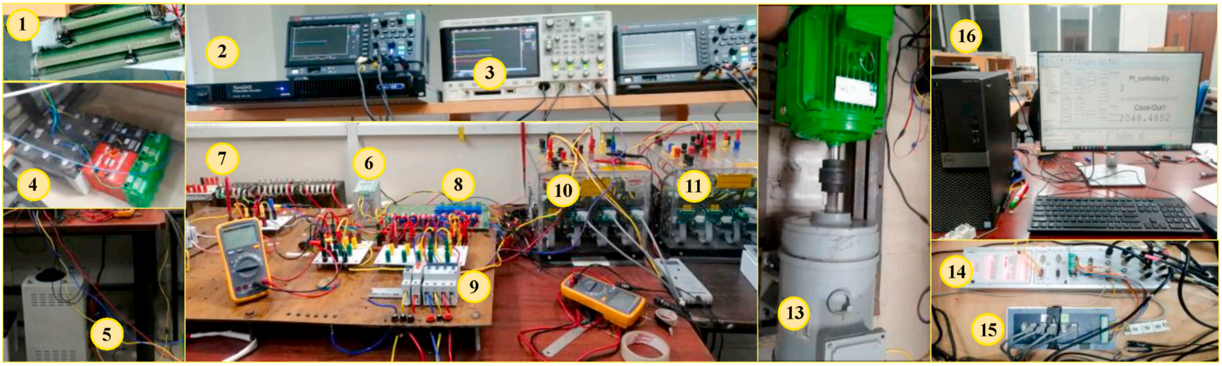

Fig. 9. Experimental prototype. (1) DC loads, (2) PV simulator, (3) oscilloscopes, (4) batteries, (5) auto transformer, (6) auxiliary DC power supply, (7) inductors, (8) current and voltage sensors, (9) MCBs, (10) three-phase inverter, (11) bidirectional converter, (12) voltage sensors, (13) coupled PMSM and DC machine, (14) dSPACE controller, (15) level shifter, (16) Computer.

Table 5
System parameters.

Parameters	Values
DC-link voltage	250 V
Battery capacity and voltage	40 AH, 98 V
Battery current	20 A
PV MPPT Voltage	102 V
PV MPPT Current	4.8 A
DC-link Capacitor	2200 μ F
Inductor for battery converter	20 mH
Inductor for PV converter	20 mH
Grid side filter inductor	30 mH
Grid voltage	120 V RMS

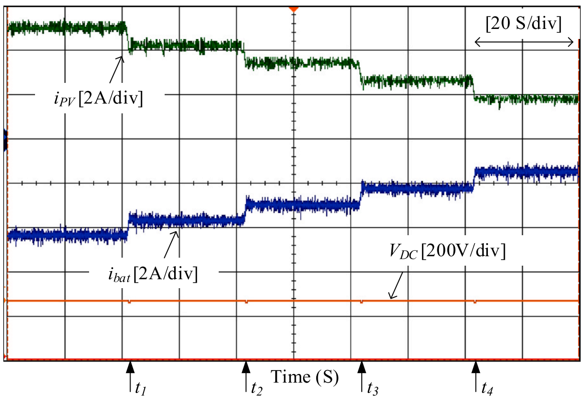

Fig. 10. Case 1: PV feeds power to the battery under different solar irradiance. (i.e., PV=ON, battery = ON, pump = OFF, AC grid = OFF).

i_{stator} are 9 A and 9 A, respectively.

5.4. Case 4: pump load with PV and AC grid

In this case, the PV and AC grid both feed the power to the IPMSM. Fig. 14 illustrates the PV, AC grid and IPMSM performances for this case. Solar irradiance is kept constant throughout i.e., 400 W/m^2. Initially PV and AC grid both present in the system till t_{10}. During this time, PV feeds power to the AC grid and it can be seen through section Z_5. Here, i_g and V_g both are out of phase from each other. Later, at t_{10} the IPMSM is connected and begin to run then reaches to 500 RPM in steady-state. In steady-state, the V_{PV}, i_{PV} and i_g are 107 V, 2 A and −0.5 A, respectively. After some time, at t_{11}, the speed of IPMSM is increased up to 1000 RPM. This increment in the speed requires extra power than PV. Therefore, AC grid start to deliver power and feed to IPMSM. A change in i_g can be seen in zoomed

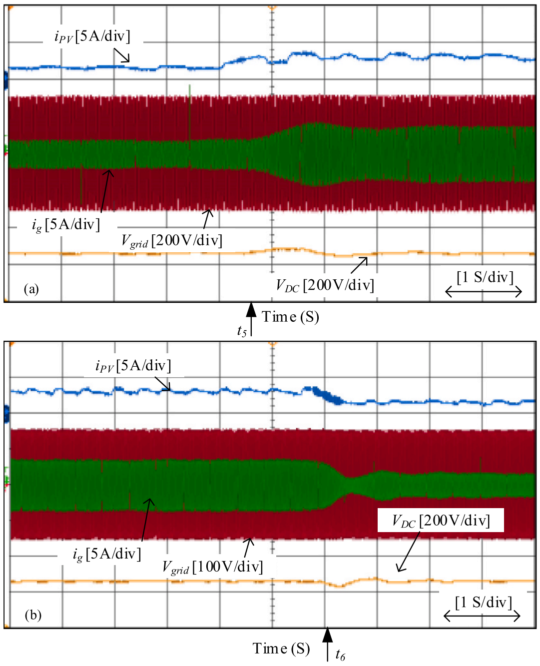

Fig. 11. Case 2: PV is connected to grid. During (a) increment and (b) decrement in solar irradiance. (i.e., PV=ON, battery = OFF, pump = OFF, AC grid = ON).

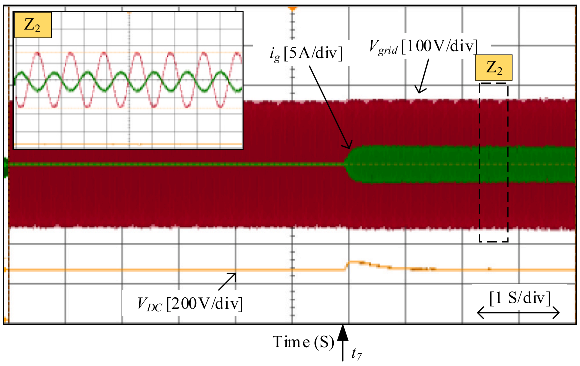

Fig. 12. Case 2: Transient during turning ON of PV.

version Z_6. Here, i_g is changed from −0.5 A to 6.5 A when speed changes from 500 to 1000 RPM.

5.5. Case 5: pump load with battery

A situation can be arisen when both PV and AC grid is not available and irrigation is needed. At this time, battery feeds the power to IPMSM. The steady state performances of battery and IPMSM at 500 RPM and 800 RPM, respectively are illustrated in Fig. 15(a) and (b). At t_{12}, it can be observed that as the motor speed increases from 500 to 800 RPM, the battery current i_{bat} also rises from 3.5A to 8 A.

6. Conclusion

An energy management scheme is proposed for PV-battery based grid-connected system to drive the water pump. This helps to make water and energy-saving reliable irrigation system. The proposed scheme is based on data such as rainfall, solar irradiation, temperature, and soil moisture level. These aforesaid data are used to operate solar pump based on availability of the power sources such as PV, battery and AC grid utility. In this paper, various real-time scenario such as PV with battery, PV with grid, water pump with AC grid, both PV and AC grid with water pump, and battery with water pump have been implemented experimentally. Hence, the

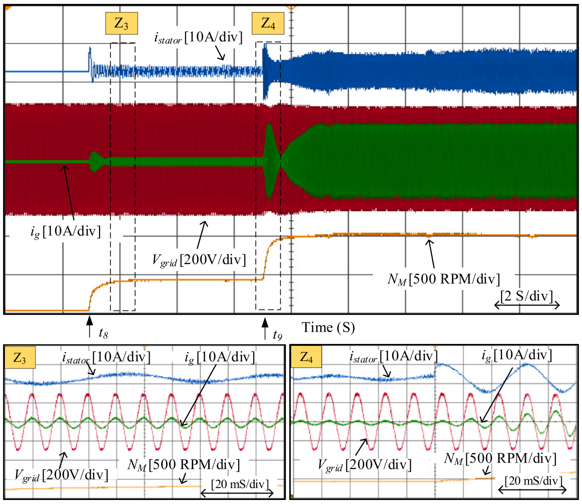

Fig. 13. Case 3: Performance during AC grid feeds power to IPMSM. (i.e., PV═OFF, battery = OFF, pump = ON, AC grid = ON).

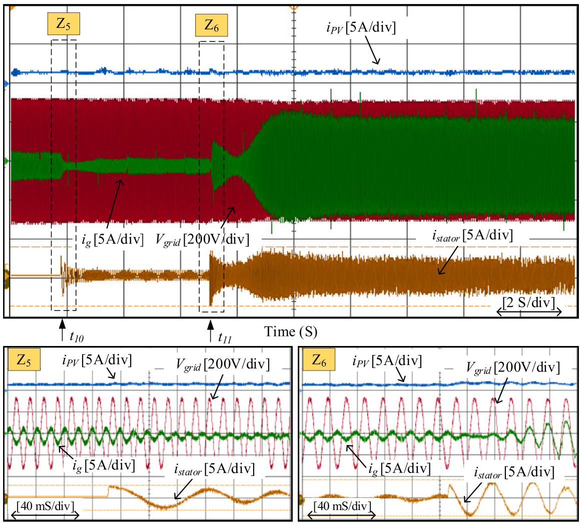

Fig. 14. Case 4: Performance during PV and AC grid feed power to IMPSM. (i.e., PV═ON, battery = OFF, pump = ON, AC grid = ON).

optimal operation of pump and harvesting maximum power from PV along with the power injection into AC grid if needed, have assured the water and energy-saving during irrigation. The results show that around 9.24 % of water and energy saving is achieved with the proposed irrigation system for potato crop with full irrigation. However, extensive studies are required to explore more water and energy saving possibilities for different crops under different levels of deficit irrigation.

Ethical standards

The research meets all ethical guidelines, including adherence to the legal requirements of the study country.

Data availability

The data used will be shared upon the request to corresponding author.

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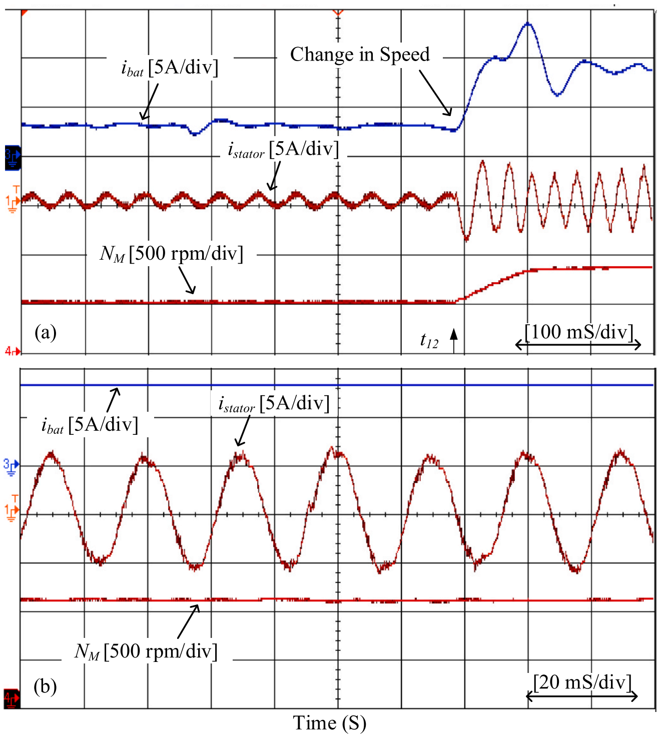

Fig. 15. Case 5: Battery and IPMSM performance at (a) $N_m = 500$ RPM and (b) $N_m = 800$ RPM. (i.e., PV=OFF, AC grid = OFF, battery = ON, pump = ON).

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CRediT authorship contribution statement

Neelesh Yadav: Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Balasundaram Pattabiraman:** Writing – review & editing, Software, Investigation, Formal analysis, Data curation. **Narsa Reddy Tummuru:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **B.S. Soundharajan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **K.S. Kasiviswanathan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Adebayo J. Adeloye:** Writing – review & editing, Visualization, Validation, Supervision. **Subhamoy Sen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mukesh Maurya:** Writing – original draft, Software, Investigation, Formal analysis, Data curation. **S. Vijayalakshmanan:** Software, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:No conflicts of interest to disclose.

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