PV Based Grid Connected Water Pumping Using BLDC Motor

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***Abstract*: This paper proposes a bidirectional power flow control of a gridinteractive solar photovoltaic (PV) fed water pumping system. A brushlessDC (BLDC) motor-drive without phase current sensors, is used to run awater pump. This system enables a consumer to operate the water pumpat its full capacity for 24-hours regardless of the climatic condition and tofeed a single phase utility grid when the water pumping is not required.The full utilization of a PV array and motor-pump is made possible inaddition to an enhanced reliability of the pumping system. A single phasevoltage source converter (VSC) with a unit vector template (UVT)generation technique accomplishes a bidirectional power flow between the grid and the DC bus of voltage source inverter (VSI),which feeds aBLDC motor .The VSI is operated at fundamental frequency, whichminimizes the switching loss. The maximum power point (MPP)operation of a PV array, and power quality improvements such as powerfactor correction and reduction of total harmonic distortion (THD) of gridare achieved in this system. Its applicability and reliability are demonstrated by various simulated results using MATLAB / Simulink platform and hardware implementation.**

Keywords: Power flow control; Solar photovoltaic; Brushless DC motor; Voltage source converter; Unit vector template; Voltage source inverter; Maximum power point; Power quality; Power factor; Total harmonic distortion.

INTRODUCTION:

The continuously increasing carbon emission and diminishing of fossil fuels encourage the instant consumers to adopt the renewable energy. A solar photovoltaic (PV) generation is emerging as the best alternative of conventional sources for various appliances. The DC motors have been used initially to pump the water followed by an AC induction motor. A permanent magnet brushless DC (BLDC) motor, due to its high efficiency, high power density, no maintenance, long service life, low electromagnetic interference (EMI) issues and small size, is being opted from last decade. It has been determined that introducing this motorreduces the cost and size of PV panels in addition to improved performance and maintenance free operation. Associated with a bidirectional control, the battery is charged and discharged during full and poor solar radiation (or no radiation) respectively, thus it ensures a full water delivery continuously. Contrary to it, introducing a battery energy storage in PV based water pumping not only increases the overall cost and maintenance but also reduces its service life. A lead acid battery which is mostly used, has a useful life of only 2-3 years. The prime attention is to achieve an uninterrupted water pumping with its full capacity regardless of operating conditions, whether day or night. A water pump along with a pump controller is connected at the common DC bus of PV array and grid connected inverter. No battery storageis used, a service life of the system is thus prolonged, and the maintenance and manufacturingcost are reduced. Although being a grid connected PV pumping system, it appears as a system operated by utility grid only. A kind of hybrid PV water pumping is presented in [15], wherein a battery is first charged by PV array through a charge controller and then it is discharged to feed the water pump via an inverter. This system becomes expensive due to an added manufacturing and maintenance cost of the battery storage. The proposed system deals with the development of a bi-directional power flow control, enabling the flow of power fromPV array to the single phase utility grid in case a water pumping is not required, and from the grid to BLDC motor-pump in case the PV array power is not sufficient (or at night) to run thepump at its full capacity. The proposed system also meets the power quality standards required by a utility grid as per IEEE-519 standard [19]. A grid interfaced PV based water pumping system, incorporating some of the aforementioned features, has been reported in [20]. A detailed design approach, control methodology, simulation analysis and hardware implementation are added here. The MPPT (Maximum Power Point Tracking) of PV array [21-25] is achieved by an incremental conductance (InC) technique using a DC-DC boost converter. The magnitude of stator current of BLDC motor at starting is controlled by operating the VSI (Voltage Source Inverter) in PWM (Pulse Width Modulation) mode for a pre-defined duration. However, once the motor is started, the VSI is operated with the pulses of fundamental frequency resulting in a minimized switching loss and an enhanced conversion efficiency. Moreover, no phase current sensor is used for BLDC motor control which leads to an increased cost benefit. The grid interactive PV based water pumping system using a BLDC motor drive is designed, modelled and simulated in MATLAB/Simulink platform, and its performances are evaluated through simulated results followed by hardware implementation to demonstrate the claims.

Three-Phase Voltage Source Inverters: Single-phase VSIs cover low-range power applications and three-phase VSIs cover the medium- to high-power applications. The main purpose of these topologies is to provide a three-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable. Although most of the applications require sinusoidal voltage waveforms (e.g., ASDs, UPSs, FACTS, var compensators), arbitrary voltages are also required in some emerging applications (e.g., active filters, voltage compensators). Thestandard three-phase VSI topology is shown in Fig. 14.13 and the eight valid switch states aregiven in Table 14.3. As in single-phase VSIs, the switches of any leg of the inverter (S1 and S4, S3 and S6, or S5 and S2) cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. Similarly, in order to avoid undefined states in the VSI, and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity. Of the eight valid states, two of them (7 and 8 in Table 14.3) produce zero ac line voltages. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states (1 to 6 in Table 14.3) produce nonzero ac output voltages. In order to generate a given voltage waveform, the inverter moves from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages that are vi , 0, and ÿvi for the topology shown in Fig. The selection of the states in order to generate the given waveform is done by the modulating technique that should ensure the use of only the valid states.

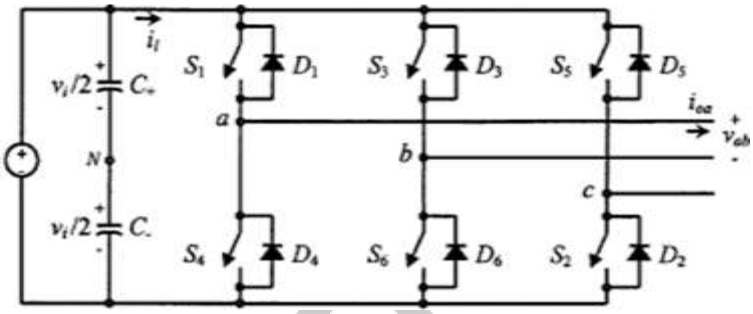


Fig. 3.1 three phase voltage source inverter

CONFIGURATION OF PROPOSED SYSTEM:

A configuration of the proposed water pumping system is presented in Fig. 1, wherein a BLDC motor runs a water pump. A PV array feeds a BLDC motor-pump via a boost converter and VSI. The boost converter performs MPPT of PV array through InC algorithm while the VSI performs an electronic commutation of BLDC motor [5, 26]. An inbuiltencoder generates three Hall-Effect signals to carry out an electronic commutation. The DC bus of VSI is supported by a single phase utility grid. A voltage source converter (VSC) enables a bi-directional power transfer through a DC bus capacitor. The PV array feeds the grid only when a water pumping is not required otherwise it is a preferred objective.An interfacing inductor is placed in the line to allow power flow between the grid and VSC, and to limit the harmonics current into the supply. A RC ripple filter is provided to limit the harmonics on supply voltage. An integrated mathematical modelling of the overall system is given in Appendices.

SPEED CONTROL OF BLDC MOTOR:

As discussed before, the proposed BLDC motor drive eliminates the phase current sensors. It is desired to operate the BLDC motor-pump at its rated speed irrespective of the climatic condition. This is achieved by continuously regulating the DC bus voltage of VSI at the rated DC voltage of BLDC motor. A bi-directional power flow control enables, by regulating the DC bus voltage and hence the operating speed, to deliver a full amount of power required to pump the water with full capacity. In case the grid is not available, the DC bus voltage is not maintained at the rated DC voltage of BLDC motor under bad climatic conditions, and the speed is governed by a variable DC bus voltage.

BI-DIRECTIONAL POWER FLOW CONTROL:

The development of a reliable water pumping system and full utilization of the resources are realized by a grid interactive PV generation. To allow the flow of power in either direction, a bi-directional power control based on a UVT generation [20, 27-28] is applied as shown in Fig. 2. This is the simplest technique and is easy to implement as it does not require any complex mathematical model or algorithm. A single phase PLL (Phase Locked Loop) is used to synchronize the utility grid voltage and current. It generates a sinusoidal unit vector of supply voltage, sin θ at fundamental frequency. On the other hand, an amplitude of fundamental component of supply current, Isp is extracted by regulating the DC bus voltage, vdc. A proportional-integral (PI) controller is used as a voltage regulator. vdc is sensed and passed through a first-order low pass filter to suppress the ripple contents. Thefiltered vdc is then compared with a set value, Vdc* . A fundamental component of supply current, is * is extracted by multiplying Isp and sin θ. The sensed supply current, is is compared with is *and error is processed through a current controller to generate the gating pulses for VSC. When it is required to draw power from utility, the voltage regulator generates a positive Isp. Therefore, an in-phase supply current is drawn from the grid. Likewise, when the utility is fedby PV array, a negative Isp is generated resulting in an out-of-phase supply current. Thus, by reversing the direction of current, direction of power flow is controlled as per the requirement. An improved power quality at the utility grid is also ensured by the applied control technique in terms of total harmonic distortion (THD) and power factor. In case the grid is not available, the DC bus voltage cannot be regulated. Nevertheless, the PV array is able to feed the water pump in standalone mode although being sensitive to the climatic condition. The detailed analysis of proposed bidirectional power flow control is given in Appendices.

SIMULATION CIRCUIT:

An analysis of the proposed system under various operating conditions is carried out through the simulated results in MATLAB/Simulink platform. The developed system and its control are tested for starting, dynamic, and steady state operations. A 4-pole, 3000 rpm @ 270 V (DC), 1.3 kW motorpump is powered by a 1.5 kWp (under standard test conditions) PV array and a single phase 180 V, 50 Hz utility grid. Detailed specifications of the system are givenin Appendices. The water pump is operated with a PV array only, with the grid only, with both PV array and grid, or may not be operated for instance. All these possible operating conditions are considered for the demonstration of proposed system.

A. Starting and Steady State Performance

The main objectives of these performance studies are to demonstrate the soft starting of BLDC motor and steady state operation of motor-pump under various operating conditions.

1) When Only PV Array Feeds BLDC Motor-Pump: Various PV array and BLDC motor- pump indices are presented in Fig. 3. As shown in Fig. 3(a), PV array is operated at its MPP under the radiation level of 1000 W/m2 . Therefore, the BLDC motor-pump is also operatedat its full capacity and it runs at rated speed i.e. 3000 rpm, as shown in Fig. 3(b). No grid power is required as the PV array generates a sufficient power to run the pump at its full capacity. The various indices refer to back-EMF, ea , stator current, isa, speed, N, electromagnetic torque, Te , and load torque, TL. These results demonstrate a soft starting along with the successfull steady state operation of the motor-pump.

2) When Only Utility Grid Feeds BLDC Motor-Pump: This operating condition occures when a water pumping is required at night. Fig. 4(a) depicts that an in-phase sinusoidal supply current of 8.3 A (rms) is drawn and DC bus voltage is maintained at 270 V. The motordraws a sufficient power from utility to run at full capacity, as shown in Fig. 4(b). A full utilization of pumping system is demonstrated in this case.

3) When Water Pumping is not required: In this case, the pump is not operated and power generated by the PV array is fed to the utility grid. Fig. 5(a) shows the MPP operation of PV array at 1000 W/m2 . Fig. 5(b) exhibits an out-of-phase sinusoidal supply current which indicates that the utility is fed by a PV array and the power flow is reversed while maintaining the DC voltage at 270 V.

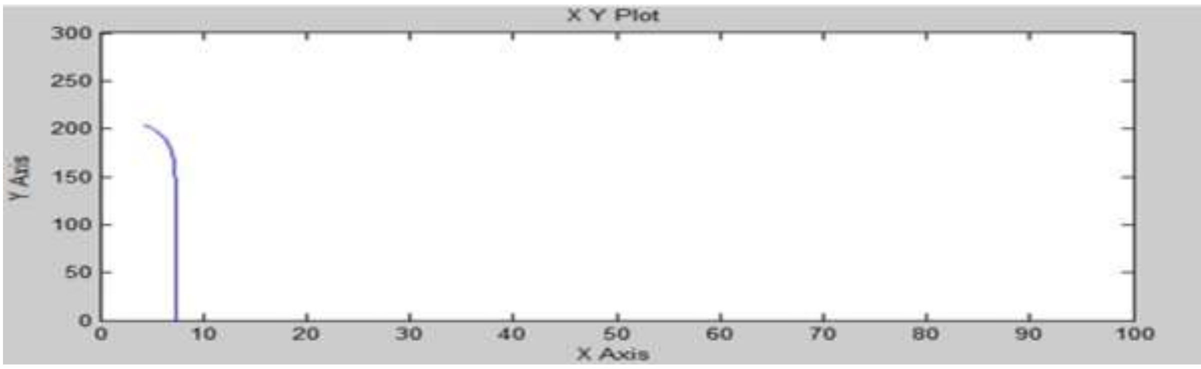
A. Dynamic Performance A sudden variation in climatic condition or requirement of sudden change in the direction of power flow, is considered as a dynamic condition. The proposed system is tested to operate successfully under the considered dynamics.

1) Transition from Grid Feeding Pump to PV Array Feeding Grid: This analysis assumes that the water pump is operated initially through utility grid when PV array power is not available.The mode of operation is suddenly changed by considering that the water pumping is no more required but PV array power is available. Therefore, it is desired now to feed the utility by PV array. Fig. 6 illustrates the performance under this dynamic condition. The mode of operation is changed at 0.3 s. Figs. 6(a), 6(b) and 6(c) respectively present the PV array indices, utility grid indices and BLDC motorpump indices. As shown in Fig. 6(b), the direction of current flow reverses within a half cycle. The DC bus voltage is regulated at 270 V as shown in Fig. 6(c). A reduction in the

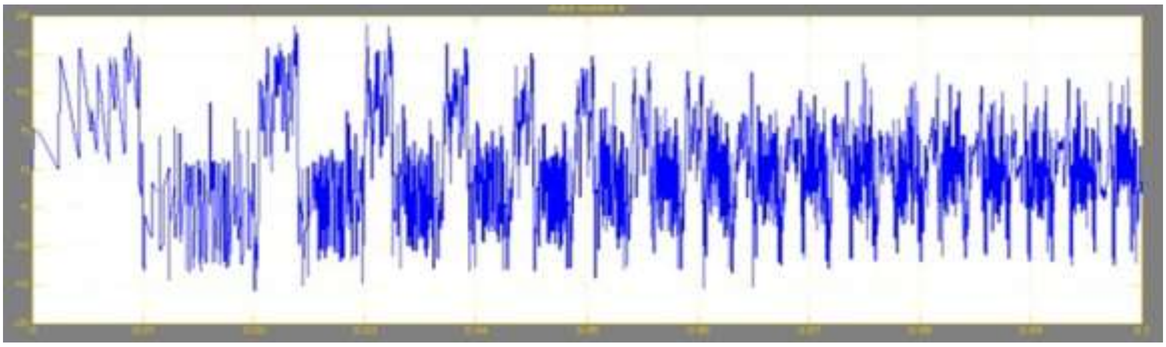
2) Transition from PV Array Feeding Pump to Both PV Array and Grid Feeding Pump: In this case it is assumed that only the PV array is feeding the pump initially as it is sufficient to run the water pump at its full capacity. A reduction in radiation level from 1000 W/m2 to 500W/m2 is observed at 0.3 s. Since the PV array alone is unable to run the water pump at its fullcapacity at 500 W/m2 , it is desired to draw the remaining power from the utility. This condition is illustrated in Fig. 7. As shown in Fig. 7(a), the maximum PV array power reduces corresponding to a radiation level of 500 W/m2 . Prior to 0.3 s, no power is drawn from the utility as shown by is in Fig. 7(b). From 0.3 s onwards, the remaining power is drawn from the utility resulting in a flow of in-phase supply current of 4.3 A (rms). Fig. 7(c) depicts that the motorpump is operated at its full capacity regardless of climatic conditions. The motor runs at 3000 rpm as the DC bus voltage is regulated at 270 V.

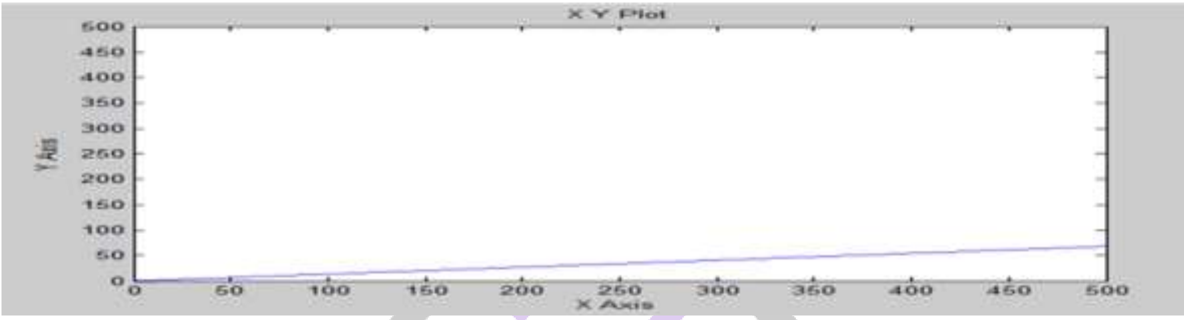
B. Power Quality Aspects The proposed system ensures an improved power qualityon the utility grid in terms of power factor and THD. Fig. 8(a) presents the THD and harmonics spectrum of supply current, is shown in Fig. 4(a), in case the water pump is fed by utility gridonly. Similarly, Fig. 8(b) presents the THD and harmonics spectrum of is shown in Fig. 7(b), in case the radiation level is 600 W/m2 and remaining power is required to be fed by the utility grid. Under both condition, THD of supply current is observed below 5% which meets the IEEE519 standard. Moreover, a unity power factor operation is ensured under the various operating conditions.

SIMULATION AND RESULTS:

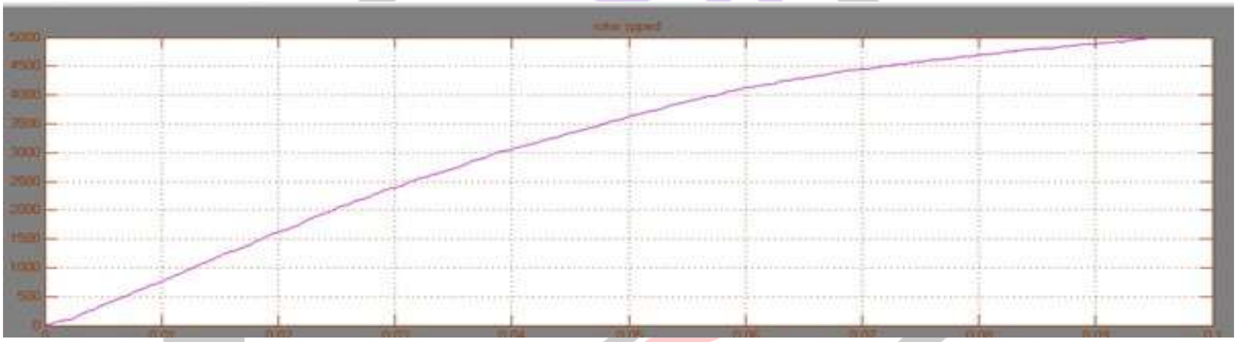


Solar IV characterizes

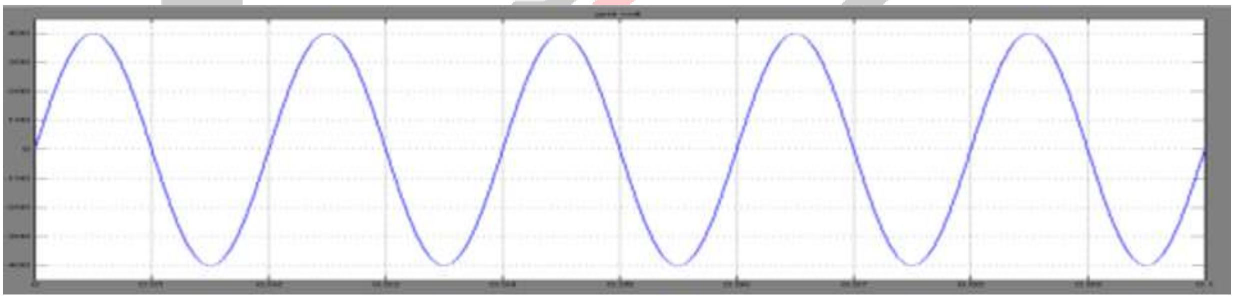

Solar PV characterizes

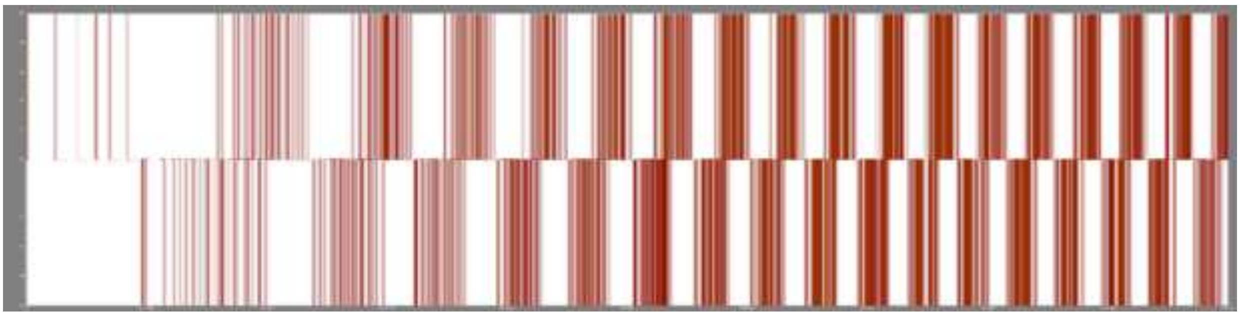


Stator current



Rotor speed


Grid input voltage


VSI output

CONCLUSIONS:

A single phase grid interactive PV array based water pumping system using a BLDC motor drive has been proposed and demonstrated. A bi-directional power flow control of VSC has enabled a full utilization of resources and water pumping with maximum capacity regardless of the climatic conditions. A simple UVT generation technique has been applied to control the power flow as desired. All the power quality aspects have been met as per the IEEE-519 standard. The speed control of BLDC motor-pump has been achieved without any current sensing elements. A fundamental frequency switching of VSI has contributed to enhance the efficiency of overall system by reducing the switching losses. The proposed solution has emerged as a reliable water pumping system, and as a source of earning by sale of electricity to the utility when water pumping is not required.

APPENDIX:

Parameters of Solar Array Peak power = 1.5 kW; Open circuit voltage = 254.8 V; MPP voltage = 200 V; Short circuit current = 8.15 A; MPP current = 7.5 A. Specifications of Motor Poles = 4; Speed = 3000 rpm; Stator resistance = 3.58 Ω; Stator inductance = 9.13 mH; Voltage constant = 68 V/krpm. Grid Interfacing Components Interfacing inductor = 3.3 mH; R-C filter = 5 Ω, 5 µF; DC bus capacitor = 4700 µF.

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