GRID INTERACTIVE SOLAR PV BASED WATER PUMPING USING BLDC MOTOR DRIVE

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Abstract This paper proposes a bidirectional power flow control of a grid interactive solar photovoltaic (PV) fed water pumping system. A brushless DC (BLDC) motor-drive without phase current sensors, is used to run a water pump. This system enables a consumer to operate the water pump at its full capacity for 24-hours regardless of the climatic condition and to feed 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 in addition to an enhanced reliability of the pumping system.

A single phase voltage source converter (VSC) with a unit vector template (UVT) generation technique accomplishes a bidirectional power flow control between the grid and the DC bus of voltage source inverter (VSI), which feeds a BLDC motor. The VSI is operated at fundamental frequency, which minimizes the switching loss. The maximum power point (MPP) operation of a PV array, and power quality improvements such as power factor correction and reduction of total harmonic distortion (THD) of grid are achieved in this system. Its applicability and reliability are demonstrated by various simulated results using MATLAB/Simulink platform and hardware implementation.

I 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 [1]. With reference to this, the water pumping has gained a broad attention in last few decades as a crucial application of PV energy [2-3]. The DC motors have been used initially to pump the water followed by an AC induction motor [4]. An innumerable researches have been carried out on electric motor drives to improve the performance and efficiency of PV fed pumping systems with cost benefit.

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 [5]. It has been determined that introducing this motor reduces the cost and size of PV panels in addition to improved performance and maintenance free operation [6]. Being a grid-isolated or standalone system, the existing BLDC motor driven water pumps fed by a PV array rely only on solar PV energy. Due to its intermittency, the solar PV generation exhibits its major drawbacks, which results in an unreliable water pumping systems. In the course of bad climatic condition, water pumping is severely interrupted, and the system is underutilized as the pump is not operated at its full capacity. Moreover, an unavailability of sunlight (at night) leads to shutdown of the water pumping system.

These shortcomings are required to be overcome in order to acquire a reliable PV based pumping system. Few attempts in this connection are found in [7-10], although not with BLDC motor drive, which deploy a battery as an energy storage. 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 [11-12].

A lead acid battery which is mostly used, has a useful life of only 2-3 years [13]. The aforementioned demerits with the battery storage have turned the attention towards an alternate technological solution which may be best suited in every aspect for a reliable water pumping based on PV generation.

These recently recognized technologies, in reality, interface a PV generating unit which is installed for water pumping, into a utility grid. The prime attention is to achieve an uninterrupted water pumping with its full capacity regardless of operating conditions, whether day or night. A grid connected solar water pumping system is reported in [14] wherein a power allocation system decides whether to draw power from PV array or from the utility (when PV array is insufficient to power the pump).

A water pump along with a pump controller is connected at the common DC bus of PV array and grid connected inverter. No battery storage is used, a service life of the system is thus prolonged, and the maintenance and manufacturing cost are reduced. However, the developed control enables only a unidirectional power flow i.e. an excess power or an unutilized power (when pumping is not required) of PV array is not returned to the utility grid.

Therefore, the PV installation is not fully utilized and a consumer must pay an electricity bill. Such another system [13] first feeds the PV energy into the utility grid through a grid inverter and a water pump is then fed by that utility grid through a pump inverter. Although being a grid connected PV pumping system, it appears as a system operated by utility grid only.

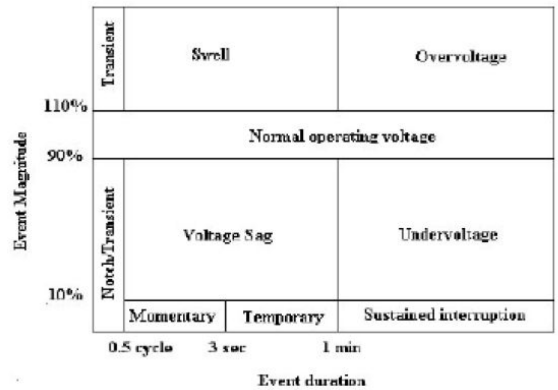
A kind of hybrid PV water pumping is presented in [15], wherein a battery is first charged by PV array through a charge controller and then it is discharged to feed the water pump via an inverter. The pump is also supported by a utility interface through an option switch. This system becomes expensive due to an added manufacturing and maintenance cost of the battery storage. A part of the PV installation is engaged in water pumping and the remaining part in feeding power to the grid in [16-17].

The system is not reliable as the pumping is dependent only on the PV energy and no power is drawn from the utility. A grid interfaced PV fed-BLDC motor driven water pumping with unidirectional power flow control is developed in [18], wherein the remaining power is drawn from the grid whenever required. The developed system fails to utilize the PV power in case the water pumping is not required.

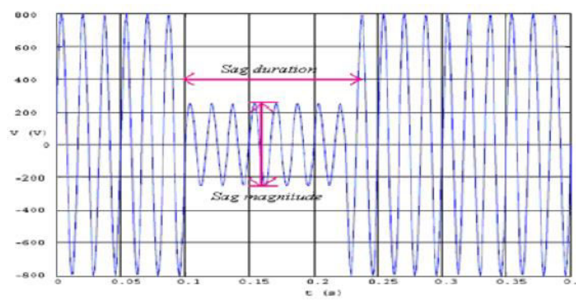
II POWER QUALITY

Power quality may be defined as the “Degree to which both the utilization and delivery of electric power affects the performance of electrical equipment.”[14] From a customer perspective, a power quality problem is defined as “Any power problem manifested in voltage, current, or frequency deviations that results in power failure or disoperation of customer equipment.”[13]

In a three-phase system, unbalanced voltages also are a power quality problem. Among them, two power quality problems have been identified to be of major concern to the customers are voltage sags and harmonics, but this project will be focusing on voltage 6 sags. Figure 2.3[10] describe the demarcation of the various power quality issues defined by IEEE Std. 1159-1995.



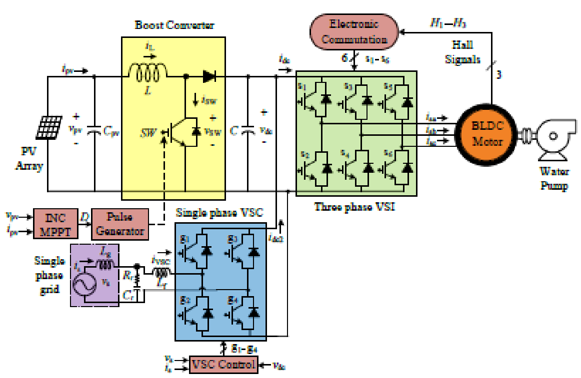
IEEE Standard 1159-1995



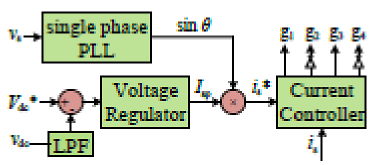
Voltage Sag Depiction

III SPEED CONTROL OF BLDCMOTOR

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.



Schematic of the grid interactive PV array based water pumping system using a BLDC motor drive



UVT based bi-directional power flow control of VSC

IV SYSTEM DESIGN

Various operating stages associated with the configuration shown in Fig. 1 viz. PV array, boost converter, single phase grid, single phase VSC, three phase VSI and BLDC motor, are selected properly in order to get a good performance with their optimum design. The design approaches of these components are given in this section.

. A. Design of PV Array

A 1.5 kWp-PV array is designed for a 1.3 kW-BLDC motor-pump. The power losses associated with the converters and the motor-pump are taken into account. The parameters are estimated at the standard test condition (1000 W/m2, 25°C, AM 1.5). A PV module-BMU/214 with an MPP voltage of 28.5 V and an MPP current of 7.5 A (complete specifications are given in Appendices) [29] is chosen to design a PV array of required capacity.

First, the voltage of PV array, at MPP, is selected in view of the DC voltage rating of BLDC motor i.e. the DC bus voltage of VSI. It is selected as Vmpp = vpv = 200 V, and the remaining parameters are accordingly calculated as, The current at peak power point

$$I_{mpp} = i_{pv} = \frac{p_{pv}}{v_{pv}} = 1500/200 = 7.5 \text{ A} \qquad (1)$$

Where ppv = Pmpp = 1500 W is the power of PV array at MPP. Series modules are as,

$$N_s = \frac{V_{mpp}}{V} = 200/28.5 = 7 \qquad (2)$$

Parallel modules are as,

$$N_p = \frac{I_{mpp}}{I_m} = 7.5/7.5 = 1 \qquad (3)$$

Where Vm and Im are MPP-voltage and MPP-current of a module. According to (2) and (3), seven modules are connected in series to design a PV array of required size.

B. Design of Boost Converter

The design of a boost converter consists of an estimation of input inductor, L. It is selected in a manner to operate the converter in CCM, irrespective of the weather condition. The duty ratio, D1 is estimated as [30],

$$D_1 = \frac{V_{dc} - v_{pv}}{V_{dc}} = \frac{270-200}{270} = 0.25 \qquad (4)$$

Where Vdc = 270 V is the DC bus voltage of the VSI. The inductor, L is estimated as,

$$L = \frac{D_1 v_{pv}}{f_{sw} \Delta I_L} = \frac{0.25 \times 200}{10000 \times (7.5 \times 0.2)} = 3.3\,\text{mH} \qquad (5)$$

Where fsw is the switching frequency of boost converter; ΔIL is ripple in the current through L, IL (= Impp).

C. Design of Three Phase VSI

A three phase VSI is used to feed the BLDC motor. Its design consists of an estimation of voltage, current and VA ratings. As the DC bus voltage is 270 V, the required voltage rating of an IGBT switch is calculated as,

$$V_{VSI} = V_{dc} \times 1.4 = 270 \times 1.4 = 378 \approx 400\text{ V} \qquad (6)$$

A voltage safety factor of 1.4 is selected to accommodate the switching transients. Similarly, the required current rating of an IGBT switch is calculated as,

$$I_{VSI} = I_{dc} \times 1.3 = (1500/270) \times 1.3 = 7.23 \approx 7.5\text{ A} \qquad (7)$$

where 1.3 is a current safety factor. Finally, the required VA rating of VSI is estimated as,

$$VA_{VSI} = V_{VSI} \times I_{VSI} = 400 \times 7.5 = 3\text{ kVA} \qquad (8)$$

D. Design of Single Phase

VSC A single-phase VSC is used to control a bidirectional power flow. In a single-phase VSC, the blocking voltage of switching devices is equal to the DC link voltage. As the DC link voltage is 270 V, the switches have to block this voltage. A safety factor of 1.4 is selected to accommodate the voltage transients due to a high frequency switching. Therefore, the voltage rating of the IGBT devices are estimated as,

$$V_{VSC} = V_{dc} \times 1.4 = 270 \times 1.4 = 378 \approx 400\text{ V} \qquad (9)$$

The VSC has a maximum current drawn from the grid or to be fed to the grid. The said current is estimated as,

$$I_{s,\max} = \sqrt{2}\frac{P_{mpp}}{V_s} = \sqrt{2}\frac{1500}{180} = 11.78\text{ A} \qquad (10)$$

where Vs = 180 V is rms value of the utility grid voltage. Thus, the maximum current rating of IGBT devices is 11.78 A. Considering a safety factor of 1.3, the current rating is estimated as,

$$I_{VSC} = I_{s,\max} \times 1.3 = 11.78 \times 1.3 = 15.3 \approx 15\text{ A} \qquad (11)$$

Finally, the required VA rating of VSC is estimated as,

$$VA_{VSC} = V_{VSC} \times I_{VSC} = 400 \times 15 = 6 \text{ kVA}$$

E. Design of Common DC Link Capacitor

The DC link capacitor, C is common to the boost converter, three phase VSI and single phase VSC. It is tuned for the second harmonic component of single phase grid voltage, which is appeared on the DC bus of a single phase VSC. Thus, the capacitor, C is estimated as [31],

$$C = \frac{I_{dc}}{2\omega_L \Delta V_{dc}} = \frac{1500/270}{2\times(2\pi\times 50)\times(270\times 0.008)} = 4700\ \mu\text{F} \quad (13)$$

where Idc is an average current flowing through the DC bus, ùL is the line frequency in rad/s, and ÄVdc is ripple in the DC bus voltage

F. Design of Interfacing Inductor

The selection of an interfacing inductor, Lf depends on the permitted current ripple ΔIVSC. It is estimated as,

$$L_f = \frac{mV_{dc}}{4af_{SW}\Delta I_{VSC}} = \frac{1\times 270}{4\times 1.2\times 10000\times (1500/180)\times 0.2} = 3.3 \text{ mH} \quad (14)$$

where modulation index, m =1, over loading factor, a =1.2, switching frequency, fSW = 10 kHz, current ripple, ÄIVSC = 20% of IVSC.

G. Design of R-C Ripple Filter

A first order high pass filter is used to suppress the switching harmonics generated by the VSC. A small R-C filter is connected at the utility grid side. This ripple filter is designed such that it offers very high impedance to the fundamental frequency component and low impedance to the switching frequency component.

In order to meet this condition, RrCr << Tsw; where Rr, Cr and Tsw are respectively the ripple filter resistance, ripple filter capacitance and switching time. Considering RrCr = Tsw/4, Tsw = 1/10000 s and Rr = 5 Ù, Cr is estimated as [32],

$$C_f = \frac{T_{sw}}{4R_r} = \frac{1}{10000\times 4\times 5} = 5\ \mu\text{F} \quad (15)$$

Thus, a series combination of 5 Ù resistance and 5 ìF capacitance is selected as a RC ripple filter.

V SIMULATION RESULTS AND DISCUSSION

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 given in 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

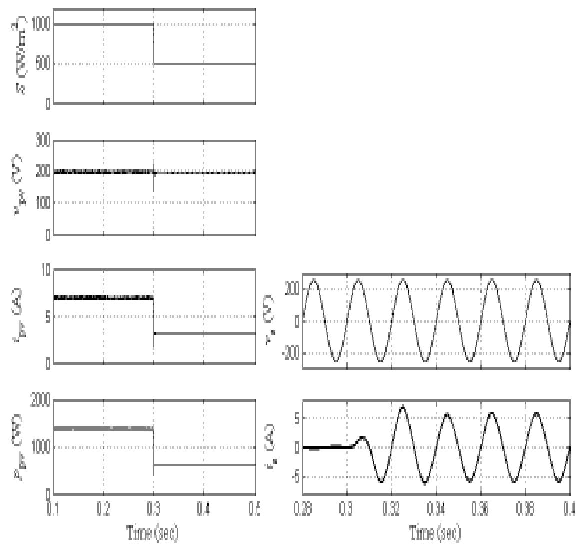
The main objectives of these performance studies are to demonstrate the soft starting of BLDC motor and steady state operation of motor-pump under various operating conditions.

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. PV array is operated at its MPP under the radiation level of 1000 W/m2. Therefore, the BLDC motor-pump is also operated at 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 success full 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. 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 motor draws a sufficient power from utility to run at full capacity, as shown in Fig. 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. 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) (b)

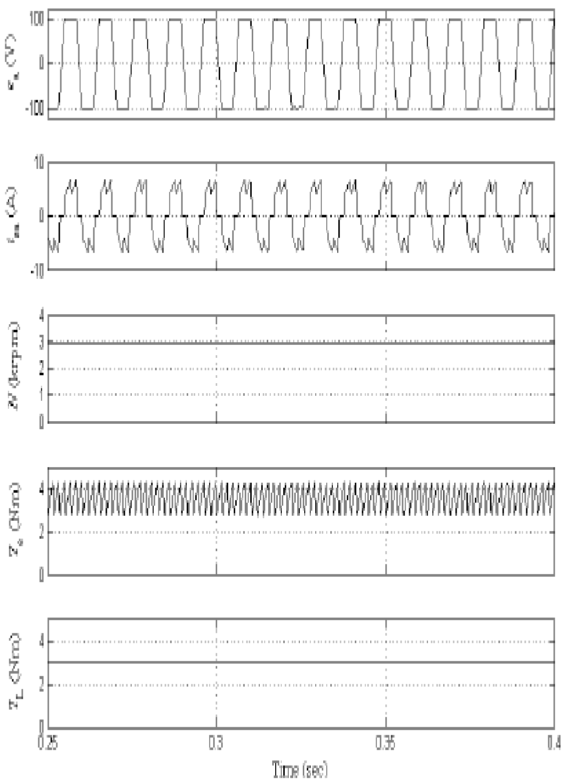
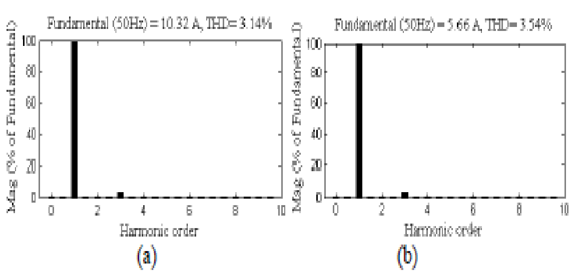


Fig Dynamic performance of (a) PV array (b) utility grid and (c) BLDC motor-pump, under a transition from PV array feeding pump to both PV array and grid feeding pump



THD and harmonic spectrum of supply current when the water pump is fed by (a) utility grid only, and (b) both utility grid and PV array

VI 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.

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