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Modelling a 30kw Standalone Solar Powered Irrigation System

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***Abstract*—The Bugesera irrigation; Rwanda utilizes the overhead irrigation system powered from national power grid to date. However, the region has an average solar energy irradiance of 5.15kWh/m^2 /day that shows PV power potential for a more efficient drip irrigation system. This study proposes an alternative highly economical, low price solar powered drip irrigation system incorporating a boost converter used to get an appropriate resolution of PWM wave forms, an inverter and an MPPT based on incremental conductance algorithm that pushes the PV panel to obtain the high peak power. The results show that the system can deliver 30kW to the solar pump for providing irrigation water for maize at the rate of 413m^3 for 3hours per day for drip and overhead irrigation of 6-9 Ha and 3-5 Ha respectively. This shows that the solar powered drip irrigation method is feasible for Bugesera irrigation scheme.**

Keywords— SPV system, MPPT, Inc.C algorithm, DC-DC boost converter, 3 level 3-phase VSC

I. INTRODUCTION

More than 80% of people in the world mainly depend on agriculture. Due to global warming and environmental degradation, rain-fed agriculture is slowly being replaced by irrigation systems in which the overhead and drip irrigation are the most common. The drip irrigation technique is the most efficient as water penetrates into the soil before it can evaporate [1],[2]. The solar energy is a good alternative source of renewable energy which is much environmental friendly and cheap [3], [4]. The solar powered pumping system can supply irrigation water without any type of additional power, e.g. diesel pumps [5],[6]. A directly coupled solar PV irrigation pump system was designed and implemented in [7]. The PV system is technically and economically viable besides low maintenance with a warranty of at least 20 years[8],[9].

A number of different maximum power point tracking (MPPT) algorithms have been proposed to increase the solar PV array efficiency. Typically, the PV array can be operated at constant voltage equal to the MPP voltage of the array at standard test conditions (STC) ignoring the effects of insolation and temperature variations on the MPP voltage [10],[11]. Perturb and observe (P&O) and incremental conductance are the most popular MPPT algorithms. As stated in [12], the P&O tracking method suffers from drift in case of an increase in insolation (G), and this drift effect is severe in case of a rapid increase in insolation. This makes P&O more inefficient compared to incremental conductance algorithm. In [13] the incremental conductance improves the P&O performance by replacing the derivative of the power versus voltage dP/dV with a comparison of the array instantaneous conductance (I/V) and incremental conductance (dI/dV). This makes the algorithm not to meander around the MPP under steady state conditions like the P&O.

In this work, a 30kW standalone solar powered drip irrigation system to supply a motor pump is modelled in Matlab/Simulink.

II. MATERIALS AND METHODS

A. Modeling of the system

The system dynamic modelling consists of; a PV array of 20 parallel strings and 5 series modules delivering a maximum of 30kW at STC (800 W/m^2, 25^{0}C), a 5-kHz DC-DC boost converter for increasing the PV array voltage from 273 Vdc to 500 Vdc, 1980-Hz 3-level 3-phase voltage source converter (VSC). The VSC converts the 500 Vdc link voltage to 260 Vac and keeps a unity power factor. The system has a 10-kvar capacitor bank for filtering harmonics produced by VSC. In order to maintain the system performance, the system includes the battery backup of 110V nominal voltage which is charged during the sunny day and can deliver power to the system during night and cloudy days.

B. PV panel modeling

The PV cell can directly convert sunlight into electricity. The voltage and current is varied according to the connected load. The load can be the lighting system, motor or pump depending on the system design. A PV module is made of solar cells interconnected to form a module at a desired voltage and the interconnection of more than one module makes a solar array[14]. The PV model equations and module manufacturer specifications given in [6],[15] have been used to build the PV system in Matlab/Simulink. The PV array block menu allows plotting of the I-V and P-V characteristics for one module and the whole array. The PV array block has two inputs that allow variation in the sun irradiance and temperature.

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The irradiance and temperature profiles are defined by a signal builder block which is connected to the PV array inputs. The proposed PV system is 30kW in which 330sunpower modules (SPR-305E-WHT-D) are used.

The array consists of 29 strings of 5 series modules connected in parallel(20*5*30.5kW). The boost converter with parameters shown in Table 1 converts solar power and injects it to the inverter as shown in Figure 1. The converter is a combination of four main components including; electronic switch, diode, inductor and outputs capacitor. The energy absorption and injection process create a switching cycle that regulates the PV array voltage to a fixed high-level value. The maximum power of the PV array is converted to DC power based on the duty cycle of the DC-DC boost converter prior to inversion to suitable AC voltage for irrigation.

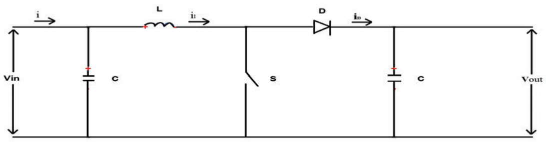


Fig. 1. Block Diagram for DC-DC Boost Converter [17]

TABLE I. MAIN DESIGN PARAMETERS OF THE DC-DC CONVERTER

Vin(v)	*Vout(v)*	*f(kHz)*	*H*
273	500	5	90%

The duty cycle is obtained from (1);

$$D=1-\frac{V_{in}(\min)\times\eta}{V_o} \tag{1}$$

Where; Vin, Vout and η are input/output voltage and converter efficiency respectively.

$$\frac{d(V\times I)}{dv}=I+V\frac{dI}{dv}=0$$

The 5-kHz DC-DC boost converter increases the voltage from the PV natural voltage of 273 Vdc to 500 Vdc. The switching duty cycle is optimized by an MPPT controller that uses the incremental conductance technique. This MPPT system automatically varies the duty cycle in order to generate the required voltage for extracting maximum power.

C. Incremental conductance MPPT

MPPT is incooperated in the DC boost converter to extract maximum energy from the PV system increasing its efficiency. The MPPT operates at a frequency ranging from 20 kHz to 80 kHz. The PV modules have relatively low conversion efficiency hence controlling MPP for the solar array systems is important [16]. Incremental conductance MPPT technique for a PV panel corresponds to the operating condition where the instantaneous conductance equals the negative incremental conductance. To obtain the maximum power output from the PV panel the incremental conductance method explores these requirements by utilizing a controller to achieve the relationship in (2) [17]. Thus, from the basic relation; $P=VI$ (2)

$$\frac{d(V\times I)}{dv}=I+V\frac{dI}{dv}=0$$

The conditions for the true MPPT on the PV curve are;

$$\frac{dI_{pv}}{dV_{pv}}=0 \tag{3}$$

$$I+V\frac{dI}{dV}=0 \qquad \text{Then,} \qquad \frac{dI}{dV}=-\frac{I}{V}$$

Where I and V are the panel's terminal current and voltage respectively; whereas dI and dV are fundamental components of I and V ripples. The integral regulator minimizes the error $\frac{dI}{dv}+\frac{I}{V}$ so that the regulator output the duty cycle correction. Figure 2 shows the incremental conductance MPPT [18] [19].

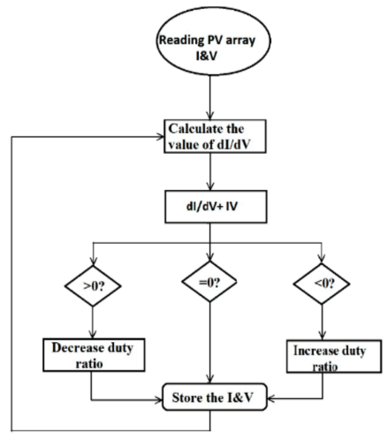


Fig. 2. Incremental conductance algorithm

In comparison with the P&O method, the incremental conductance method tracks the peak power under fast varying atmospheric conditions. It determines whether the MPPT has reached the MPP and stops perturbing the operating point. If that condition is not met, the MPPT operating point must be perturbed and calculated. This is derived from the fact that dP/dV is negative when the MPPT is to the right of the MPP and positive when it is to the left of the MPP. This algorithm determines when the MPPT has reached the MPP, whereas P&O oscillates around the MPP. The incremental conductance also tracks the rapidly increasing and decreasing of irradiance conditions with higher accuracy than P&O method [18].

D. Voltage source converter (VSC)

The VSC is used to convert the DC voltage to AC voltage for AC motor pump. The VSC converts 500 Vdc to 260 Vac and keeps unity power factor. The VSC control system operates based on constant AC voltage and frequency control mode that regulates the output voltage to the motor [22]. The control system uses a sample time of 100 microseconds. Pulse generators of the boost and VSC converter use a fast sample time of 1 microsecond in order to get an appropriate resolution of PWM waveforms.

E. Inductor selection

An inductor is used as shown Figure 1 to smooth the current ripples of the converter and store energy in each switching cycle. The inductor value is calculated using (4) [6].

$$L=\frac{V_{in}\times(V_{out}-V_{in})}{\Delta I_1\times f_s\times V_{out}} \tag{4}$$

Where; $\Delta I_1=1.75\%\times I_{out}(\max)\times\frac{V_{out}}{V_{in}}$

$$\Delta I_1 = 1.75\% \times 115 \times \frac{500}{273} \text{ then; } \Delta I_1 = 0.368$$

Inductor value is; $$L = \frac{273 \times (500-273)}{0.368 \times 5000 \times 500} = 0.0673\text{H}$$

The 10-kvar capacitor bank is used to filter harmonics produced by the VSC.

F. AC motor and pump

The solar PV panel efficiency is usually 10–18% which is very low, hence the PV power should be utilized very efficiently by selecting all solar pumping system components with optimum operating parameters. In this work a 7.5kW AC motor is connected to the water pump. The specifications of the motor and the pump are shown in the Table 2.

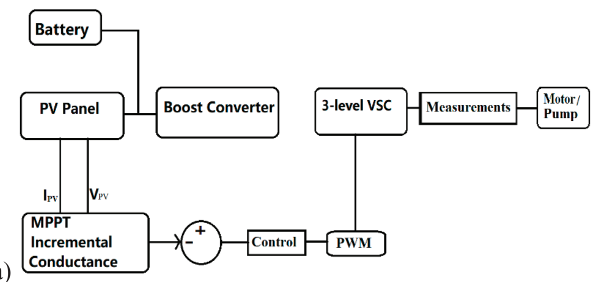
TABLE II. MOTOR AND PUMP SPECIFICATIONS

Motor/Pump specifications				
Voltage	***speed***	***Rated current***	***Rated power***	***Rotor inertia***
380v	1725rpm	20A	7500W	0.089kg.c.m^2
Voltage	***Power***	***Flowrate***	***Head***	***Model***
380V	7500W	38.2 l/s	20m	-

III. RESULTS AND DISCUSSION

A. Proposed System

The model components are assembled in Matlab-Simulink to form the proposed system in Figure 3(a) and (b). The parameters for system components were determined in section 2 and given in Table 3.0. Bugesera irrigation scheme in Bugesera district in eastern province of Rwanda is an African development Bank (ADB) sponsored project that has been in operation for over a decade where 12 HA are irrigated using overhead (sprinkler) irrigation. The overhead irrigation system which is powered from national power grid is popular to date for irrigating maize, cassava, tomatoes, etc. The Bugesera has an average 5.15kWh/m^2/day solar energy insolation that can be adequate for the proposed solar powered drip irrigation system.



a)

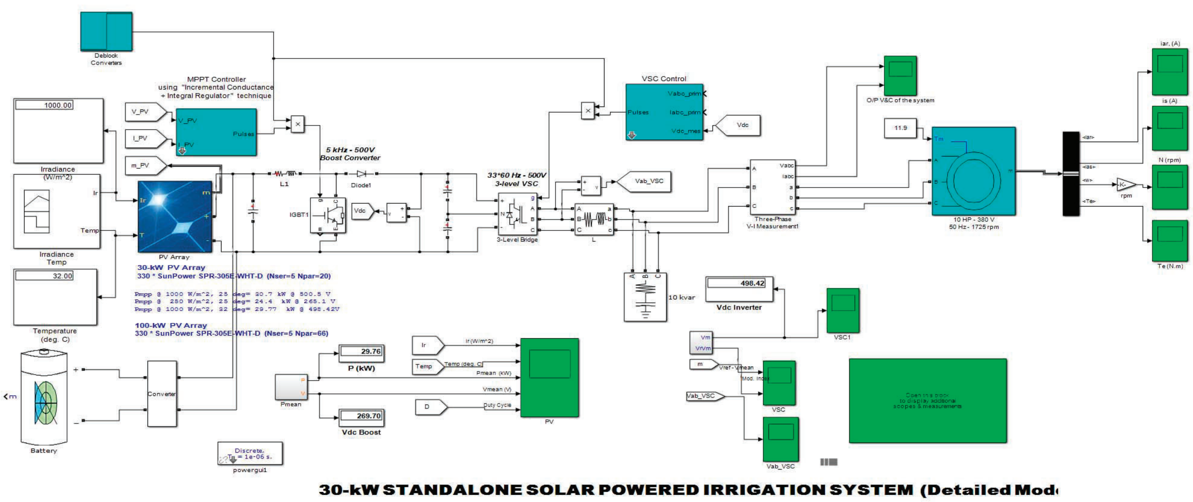


Fig. 3. Proposed; (a) Block diagram (b) System in Simulink

TABLE III. SOLAR PV MODULE SPECIFICATIONS USED IN THIS SYSTEM IN MATLAB/SIMULINK

Parameters	***Nominal values***
Peak power W	305
Max power voltage mp	54.7
Max power current Imp	5.58
Open circuit voltage Voc	64.2
Short circuit current Isc	5.96
Module efficiency %	14%
Ns	5
Np	20
Diode saturation current IL	6.3014e-12
Diode ideality factor	0.84504
Shunt resistance Rsh	269.5934
Series resistance Rs	0.37153
Light generated current	6.0092

B. Matlab/simlink simulation

Figure 4 to 8 show the relationship between the irradiance and PV power output. The incremental conductance MPPT is enabled at t=0.4 sec, the MPPT regulator starts regulating PV voltage by varying the duty cycle in order to extract maximum power output. Maximum power is 30.73 kW obtained when duty cycle is D=0.5, T=25^{0}C, the solar irradiance Ir=1000W/m^2. At t=0.6 sec, the PV array mean voltage (Vmean) =273.59 V as expected. From t=0.6 sec to t=1.1 sec, the sun irradiance at the PV array decreases from 1000W/m^2 to 250W/m^2 but the MPPT continues to track maximum power.

At t=1.2 sec since the irradiance has decreased to 250 W/m^2, the duty cycle of the boost converter is D=0.21. The corresponding PV voltage and power are Vmean= 248 V and Pmean=9.3 kW. In this case the MPPT continues tracking the maximum power during this fast irradiance change. From t=1.2 sec to t=2.5 sec, the sun irradiance is restored to 1000 W/m^2 and the temperature increase to 32^{0}C. From the results, the impact of MPPT on the PV system output when irradiance and temperature increase or decrease is obtained where the array output power decreases from 30.7 kW to 29.76 kW when the temperature increases from 25^{0}C to 32^{0}C and the MPPT continues tracking maximum power.

The boost converter is de-blocked at t=0.05sec. the boost converter and the DC link capacitors are charged to 530 V during starting transients as displayed in Figure 7(b), but later regulated at Vdc=500V as shown in Figure 6(b). The duty cycle of boost converter is fixed to D= 0.5 and the steady state of the system is reached at t=0.25s.

The inverter supply characteristics to the motor are shown in Figure 8. It can be observed that constant AC voltage and current is fed to the motor which enable it operate at the rated speed and torque.

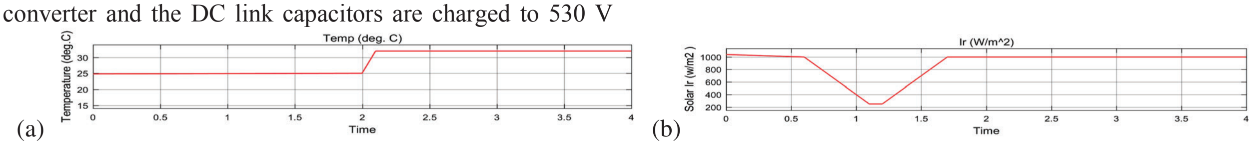


Fig. 4. Environmental Conditions; (a) Temperature input in ^{0}C (b) Solar Irradiance input in w/m^2

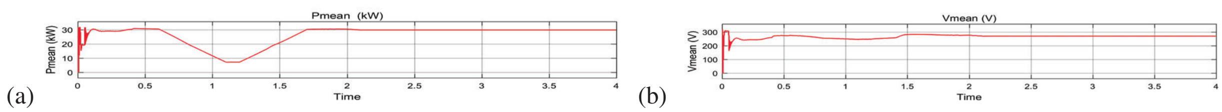


Fig. 5. PV array output: (a) Power (b) Voltage

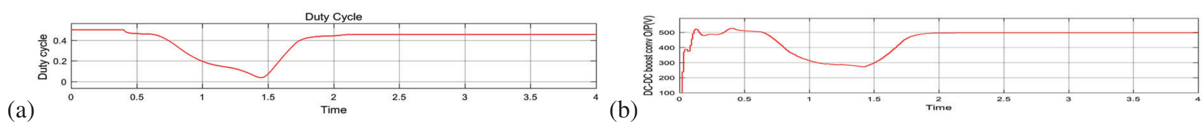


Fig. 6. DC-DC boost converter: (a) Duty Cycle (b) Output Voltage

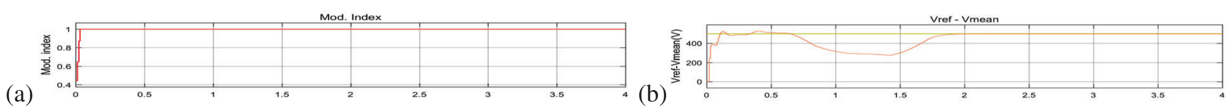


Fig. 7. VSC input: (a) Modulation index (b) Output Voltage

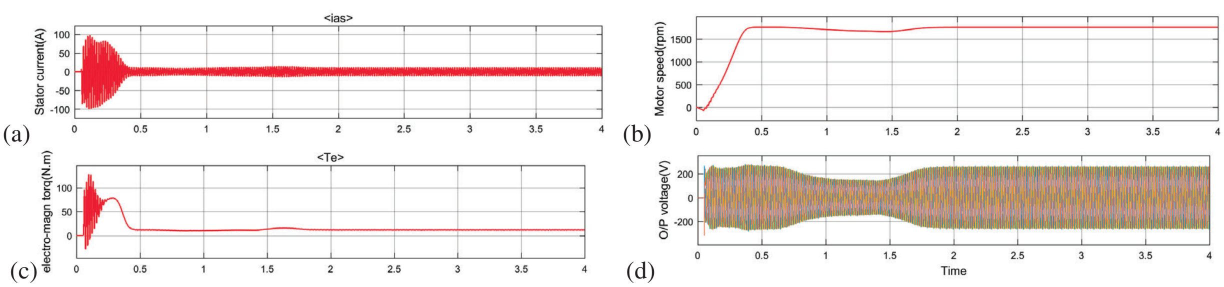


Fig. 8. AC Motor pump Characteristics: (a) stator current (b) pump speed (c) motor torque (d) inverter output voltage

C. Irrigation system

The 7.5kW AC motor was designed and connected to the water pump to deliver water 3hrs per day at a system head of 20m via drip irrigation system. From the formula of the horse power [20];

$$P_w = \rho g Q H \qquad (5)$$

where; Pw is the horse power, Q is the flow rate in m^3/s, g: is the gravity constant in m^2/s which is 9.8 m^2/s, H: is the head of the system=20m and ρ: Density of water

Taking ρ=1000Kg/m^3 and transforming Eq.5 into kilowatts;

$$P_w = \rho g Q H = \frac{\rho g Q H}{1000}$$

$$= gQH \text{ in kW}$$

The horse power Pw transferred to the motor pump is 7.5kW(10HP). Therefore, ignoring the friction losses, the following pump parameters are calculated:

The pump flow-rate;

$$Q = \frac{P_w}{gH} = \frac{7.5}{9.8 \times 20} = 0.038 m^3/s = 38.2 l/s$$

Since the pump works 3hours per day, the total water to be pumped during the irrigation time is given as;

$$\text{Total water to be pumped} = Q \times 3 \times 3600$$

$$= 38.2 \times 3 \times 3600 \frac{1}{1000} = 412.50 m^3$$

The pump efficiency;

$$\eta_p = \frac{P_w}{BHP} \quad (6)$$

where; break-horse power (BHP) is;

$$BHP = \frac{100QH}{3960} \quad (7)$$

$$BHP = \frac{100 \times 38.2 \times 20}{3960} = 19.29$$

The efficiency of the pump can be calculated by replacing HP by BHP in (13).

$$\eta_P = \frac{P_w}{BHP} = \frac{10}{19.29} = 0.52 = 52\%$$

D. Irrigated area

The 30kW standalone solar powered drip irrigation system was designed to irrigate maize. The water requirements maize in [21] is 400-600 gallons per 100ft of row per week for drip irrigation. For overhead irrigation, 700-1000 gallons per 100ft of row per week is required to irrigate maize.

For drip irrigation:

400gallons/100ft/week=75.1gallo/100ft/week and 600 gallons/100ft/week=85.7 gallons/100ft/week

Which; 0.216m^3/100ft/day and 0.324 m^3/100ft/day

Since the total water from the pump system 3hours per day is 412.50m^3, the rows irrigated are;

$$\frac{412.5}{0.216} = 1909\text{rows} \qquad \frac{412.5}{0.324} = 1273\text{rows}$$

In this irrigation scheme, the maize spacing of 83.48rows per acre(1acre=0.4047Ha) in [22]was applied. The area irrigated is given by:

$$\frac{1909 \times 0.4047}{83.48} = 9.25\text{Ha} \qquad \frac{1273 \times 0.4047}{83.48} = 6.17\text{Ha}$$

For overhead irrigation:

The rows irrigated using 412.50m^3 of water in 3hours per day is given as: 700gallons/100ft/week=100gallons/100ft/week to1000 gallons/100ft/week=142.9 gallons/100ft/week

Which; 0.379m^3/100ft/day to 0.54 m^3/100ft/day

$$\frac{412.5}{0.379} = 1088.4\text{rows} \qquad \frac{412.5}{0.54} = 763.9\text{rows}$$

$$\frac{1088 \times 0.4047}{83.48} = 5.27\text{Ha} \qquad \frac{763.9 \times 0.4047}{83.48} = 3.7\text{Ha}$$

IV. CONCLUSION

The efficient system to drive the water pump is modelled in Matlab/Simulink software, the system consists of pv panels and battery as source of power. Using the MPPT based on incremental conductance technique the high peak power is captured from PV. The research done in this paper investigated the feasibility of using PV panel to supply the water pumping system for irrigation system. Simulation results and mathematical calculations showed that the proposed 30kW system can pump 413m^3 of water in 3hours for drip irrigation of 6-9 Ha of maize with excellent controller dynamic performance. Battery is included in the system to provide power when there is no enough irradiance. The system can work on 3-5 Ha of maize on the overhead irrigation.

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