Optimization of Solar Photovoltaic Water Pumping System

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Abstract— Solar Photovoltaic Water Pumping System, as an integrated system of PV, Variable frequency drive and pumping system, which deals with the simulation and design of an effective pumping system. Thus the techniques of modeling and photovoltaic theoretical studies can be obtained by using equivalent circuits. The system also includes the maximum Power point tracking (MPPT), which can add efficiency to the total system. This paper presents the effective way to optimize the Solar photovoltaic Water Pumping System (SWPS) through both by simulation and by using a practical setup and thus evaluating the whole system performance. However the system also includes DC-DC converters for the proper voltage conversion and operation. Thus the whole SPWS system is being simulated through MATLAB, so the comparative study can be done on the performance of the system. Here the simulation in MATLAB verifies the system and MPPT functionality. Incremental Conductance (IC) method is used for maximum power point tracking (MPPT). The maximum Power variation is due to both irradiance and temperature. Since the conversion efficiency of PV Array is very low, it requires maximum Power point tracking (MPPT) control techniques. Thus every VFD's will power with MPPT Technology. This basically deals with Total System evaluation, which will be optimized based on the obtained water output for the given DC Power input.. The simulation results were carried out to verify the effectiveness of the proposed Scheme improved the performance of the systems.

Key words: Solar photovoltaic Water Pumping System (SWPS), Maximum Power Point Tracking (MPPT), Incremental Conductance (IC), Variable Frequency Drive (VFD), Permanent Magnet DC Motor (PMDC), Brushless DC Motor (BLDC), Perturb & Observe (P&O)

I. Introduction

A water pumping system will be in need of a power source for proper operation. In general, the system powered with AC source will be economic and will require minimum maintenance, when a Power grid is nearby and easy availability of AC power. But sources of water in rural areas are located too far and to obtain the power is difficult. Thus installation of new transformers and transmission lines seems expensive.

Thus all these unwanted factors can be minimized by renewable energy technologies application, more economic than fossil fuels in comparison. When it comes to reliability PV system is top in it, due to offering of lowest life-cycle cost. To extract water distinct applied sciences are being used, however using sun vigor from PV supply to function the water pumps is now a developing and leading technological know-how, which increases the involvement with science. This process with a purpose to make the life less difficult for far off and rural peoples, which also allow them to increase their revenue. Cost concerning it is going to be the only barrier on this approach.

Solar Water Pumping System is a 'Total integrated system' of Solar Photovoltaic Arrays as a DC Source, Variable Frequency Drive / Inverter and Pump Set. This SPV water pumping systems are reliable. It is under the project of, Ministry of New and Renewable Energy (MNRE) Government of India. The MNRE is developing a practice to frequently keep an eye on penetration of sun technology in the nation each at a decentralized and centralized level below the identify Jawaharlal Nehru National Solar Mission (JNNSM).

The mission aim or role is about rural areas implementation of photovoltaic water pumps that runs through the originated power from the sunshine. The sun irradiance energy is being converted to electrical power with help of Solar Photovoltaic modules. Thus these DC power output varies according to the variation of irradiance behavior. During morning session of low irradiance the generated power will be lower when it compared with the afternoon and evening sessions. As a result, there will be a variation of water discharge for different heads. Thus the amount of water discharged or volume of water obtained specifically depends on the available solar energy during that time. Specifically, depend on the particular irradiance fall on the PV modules and the size of the PV Array installed is the two things which determine the flow rate of water pumped. Intensity of Solar radiation will be higher in hot weather conditions when compared to cold situations, thus amount of water discharge will be higher in this case. Obviously when the sun is less intense leads to lower power with output water discharge. Thus SPV system is the best in rural remote areas for water extraction process, which will be more practical when comparing with other methods of water extraction, where there is a scarcity of electricity. The pumping and storing of water in a reservoir during the day time leads to assurance of water availability during night time. Strategy of storing water is more useful, practical, environmental and economic than storing electricity in batteries.

An effective method to drive DC category motor from the photovoltaic's has been designed and implemented in MATLAB/ Simulink software. And the system is avoided with the batteries or any storing devices. Using MPPT (incConductance method) technique extraction of maximum power can be obtained from panel. Modeling of each and individual component is required in order to simulate the whole SPV water pumping system in MATLAB. Thus for a DC pump motor model, here SIMULINK is employed at first and then model is transferred in to MATLAB. Then the system will be verified by the MATLAB simulations and also the functionality of MPPT.

By using an experimental setup the SPWS system behavior is observed, and how the flow varies in accordance with the different heads and pressures is been examined. And MPPT tracking is observed practically and compared with the MPPT simulation in MATLAB. The way to optimize the total system is the main task, by having an estimation and comparison of each and every point with technically and economically. For example a proper PV power of certain KW, selecting a 300W of individual module, which is being arranged in series parallel configuration for required power, is directly loaded to the motor of proper load though the inverter. At last the graphs of variation of speed, torque & back emf of the motor with proper control of MPPT algorithm is obtained approximately and compared with the practical observations. Finally the system is made optimized by comparison of proper water discharge and which can be estimated or viewed by seeing the simulated speed, torque curve and MPPT maximum power capture.

II. PHOTOVOLTAIC AND WATER PUMPING SYSTEM

A. Pv System

An equivalent Solar cell circuit consisting of a source current in parallel with a diode and a shunt resistance, connected to a series resistance. For higher power output of PV modules is preferred for enhancement of the required water output or performance of the motor. Increasing Rs decreases Pmp, Vmp, and Imp, and also reduces Fill Factor and Efficiency. Whereas decreasing Rsh decreases Pmp, Vmp, and Imp. Thus which states that shunt resistance of a module should be high and series resistance should be low for a module to give a better Power and Voltage. Thus on observation with respect to solar irradiance one can come to the point that, on maximum irradiance power output will be higher when compared with the power produced on lower irradiance. And also maximum irradiance will not affect the voltage parameter. Thus in same way if we see the response of a module to temperature increasing cell temperature results in a decrease in voltage and power, and a small increase in current.

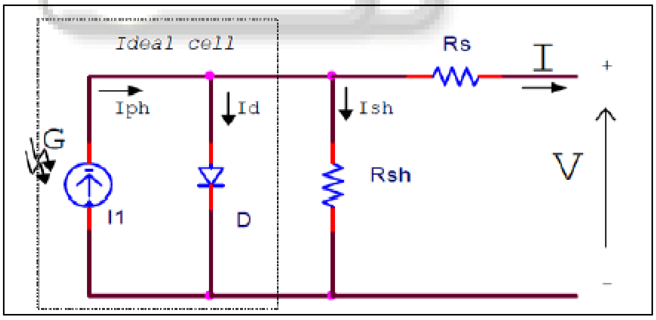

Fig. 1: Equivalent PV module circuit

By applying the Kirchof's current law (KCL) to the above equivalent PV module circuit, the output current can be determined as:

$$Ishc - Id = I$$

Where: Ishc is the Photon generated current which equals the current of short-circuit, and Id is the shunted current through the intrinsic diode.

From Shockley's equation of diode, the shunted diode current Id can be obtained as follows:

$$Idro\left(e^{\frac{qVd}{kT}} - 1\right) = Id$$

Where: Idro is the reverse saturation current of diode.
q is the electron charge (1.602×10-19 C),
Vd is the voltage across the diode (V),
k is the constant of Boltzmann (1.381×10-23 J/K),
T is the temperature of junction in Kelvin (K).

Thus replacement of Id in the main equation to get output current of PV Cell

$$Ishc - Idro\left(e^{\frac{qVd}{kT}} - 1\right) = I$$

And under open circuit conditions, diode reverse saturation current Io will be constant under constant temperature. Thus from above, in open circuit condition I=0 and solving for Io gives:

$$Ishc - Idro\left(e^{\frac{qVd}{kT}} - 1\right) = 0$$

$$Ishc = Idro\,(e^{\frac{qVd}{kT}} - 1)$$

Hence a better observation from the above equation, a current generated from the photon is equal to short circuit current Ishc, which is directly proportional to irradiance and illumination intensity. Hence by obtaining a value of Isc under the standard test condition, Go=1000W/m2 at the air mass (AM) = 1.5, then the photon generated current at any other irradiance, G (W/m2), is given by:

$$Ishc\ I_G = \left(\frac{G}{Go}\right) Ishc\ I_{GO}$$

The PV modules of mono/ multi crystalline silicon solar cells are incorporated in the PV array for the SPV water pumping systems, where the PV modules efficiency is minimum 14% and fill factor must be more than 70%.

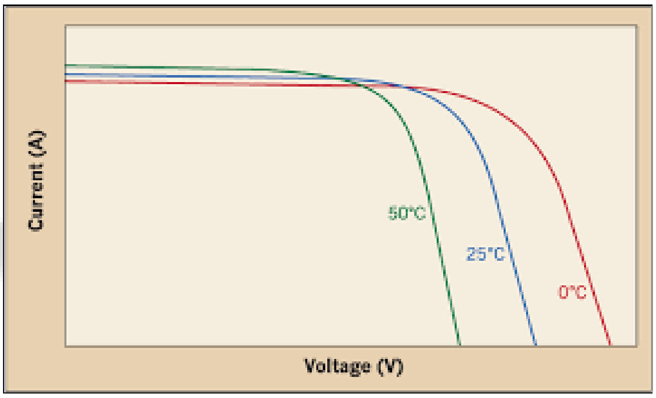

Fig. 2: Temperature effect on Voltage

Fig. 2. shows an average PV arrays V–I curve for an alternating conditions. Thus within the curve, the variation of voltage and current upon generation gives out the variable power output. The voltage decreases upon increase of temperature and current increases upon increase of irradiance. It's miles proven that the PV array V-I curve affected by the respective conditions of temperature and insolation level. Air mass also plays a role in generation of power through irradiance. For standard conditions air mass value taken as 1.5. Air mass is nothing but the distortion in the air like noise, dust and refractive or absorption of waves in between the sun and earth leads to decrease in irradiance value and which directly effects on the power generation. Thus for a module to determine its maximum power generation capacity in a Standard Test Condition is as follows: Air mass of 1.5, Temperature of 25˚C, and irradiance of 1000 W/m2.

The tilt angle is the angle created from the horizon to the sun. Sun PV modules will produce the maximum strength when the sun is shining immediately onto them, from a 90 diploma perspective. Consequently, all else identical, for fixed PV modules the nice tilt angle may be similar to the latitude of the site. Hence for example, if the PV site is at 36 N, the best tilt will be 36 degrees.

B. Motor-Pumpsets

The SPWS system basically with two types: Surface mounted and Submersible motor pump sets. But here a major concern has been taken to optimize the submersible motor pumps sets rather compared to the surface mounted pump sets. Thus for high volume discharge and efficiency perspective the centrifugal pumps will be chosen. But now a trend is being changed and running towards brushless DC motors for higher performance, efficiency and low maintenance. Hence the cost of a system will be high enough. Different type of motors will be used for operation among AC motors. However induction motors are commonly used as a AC motors because of its cheapness and availability worldwide. Generally, DC motors are preferred because which can be connected to PV output directly without any requirement of conversion devices in between and also of its high efficiency. Thus for a DC brush type motors, brushes are replaced very periodic for around every two years which will be very inefficient.

Usually among SPV system, they employ DC motors due to the fact they might be immediately coupled with PV arrays and make the system simple. Among different types of DC, an permanent magnet DC (PMDC) motor is desired in PV structures because it can offer better beginning torque. Whilst the motor is popping, it produces lower back emf (E) that is a voltage proportional to the angular speed of the rotor.

Thus for any AC Synchronous speed of a motor on equation:

$$Synchronous\ Speed = \frac{120\ X\ Frequency}{No.\ of\ Poles}$$

Hence speed of alternating current motors depends on below points,

- Based on the number of poles, the motor base speed can be achieved
- AC line voltage frequency
- Slip caused due to torque loading.

III. INVERTERS / CONTROLLERS

The condition for a motor to run with a required speed or torque requires a sufficient forward voltage to be maintained. This can be easily done through the inverters on the technique of voltage to frequency ratio (V/f), on attaining a maximum frequency around 50Hz and a required voltage which will be a constant value maintained throughout. But within the motor, this voltage is regarded as an air hole voltage.

Thus for successful operation of these VFD on applying to any motors requires some of the considerations, is as follows:

- Effective cooling ability of motor will be reduced on slowing down. Thus an external air forced ventilation or motor over-sizing is required in slow running conditions and when loads are high.
- Mechanical resonance will be generated upon different speed of operations.
- The equipment and distribution system is affected by generation of harmonic voltage and current from VFD, which can cause major blow.

Fig. 3: Power smoothing Controller

The dramatic drop in VFD efficiency will be observed, as there is any increase in temperature and may require an installation of a cooling mechanism. That can be obtained by adding an external heat sinks or self-contained cooling systems. Other factors which are going to affect the VFD efficiency are stated below.

- Radio frequency or stray high frequency signals.
- Line voltage variation greater than ±10%.
- Altitude greater than 3,300 feet (1000 meters).

Most widely the VFD's are classified in to three major types. Current supply inversion (CSI) most widely utilized various industrial purposes and signal processing. Only regenerative power capability can be found in CSI types. CSI VFDs provide an extraordinarily easy present waveform but require enormous, steeply-priced inductors in their development and intent cogging (pulsating motion during rotation) fewer than 6 Hz. Voltage supply inversion (VSI) drives which are non-regenerative and can cause motor cogging below 6Hz. Thus, CSI and VSI drives have not been commonly used.

In this era the Pulse-width modulation (PWM) technique is vastly used for obtaining no cogging of motor, with high efficiencies and benefit of fixed DC bus voltage. An ideal sinusoidal wave is obtained by PWM VFD on using voltage pulses in series, which yields a best sinusoidal because of very well timed pulses.

A. Maximum Power Point Tracker (Mppt)

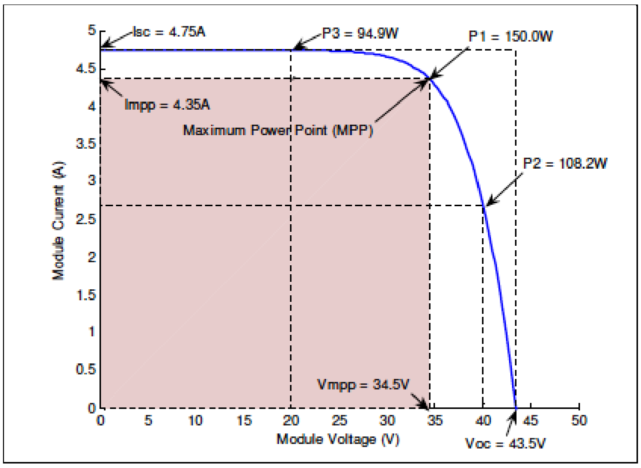

Fig. 4: MPPT circuit capturing the maximum power of a module

The most important one is the solar pump inverter with MPPT function, according to the sunlight intensity; solar pump inverter adjusts the output frequency automatically to achieve maximum power point tracking. Non-linear I-V and PV characteristics are exhibited. Based on two factors of temperature and irradiance the maximum power generated will be depends. Considering fact that most effective conversion of PV Array could be very low, thus it requires MPPT system and technique for proper operation. For achieving the maximum power interface of sunlight in any changing atmospheric conditions, it is very much necessary to have a tracking algorithm with MPPT. Thus which is one of the most important factor to evaluate the design performance of PV methods.

B. Dc-Dc Converters

Many different topologies used in this type of Converters, which has been divided in to non-isolated and isolated topologies. Isolation transformers will not be present in Non-isolated topologies. These are mainly seen in DC-motor drives. These are again categorized in three types: step up (boost), step down (buck) and step up & down (buck-boost).Hence to step up voltage boost topology and for stepping down voltage buck topology will be selected. In application of PV, charging batteries and current booster for water pumping systems the buck converter is used majorly. Boost type converter will be preferred in grid tie systems to step up voltage for matching level of utility. Hence configurations which are capable of stepping-up/down the voltage such as: buck-boost, SEPIC and Cuk.

C. Cuk and Sepic Converters

For providing high current at starting for water pump the yield voltage supposed to be stepped-down, in Water pumping systems. Thus buck converter plays a major role here. Capacitive isolation will be provided by both Cuk and SEPIC, gives protection against failure of switch. Input current is continuous in Cuk and SEPIC topologies, thus the ripple free current can be drawn from array of PV which is essential for the proficient working of MPPT. The Cuk converter can provide yield voltage which can be lower/higher than input voltage. Derivative of Cuk converter is the SEPIC converter. The topology of both characteristic's is similar. In both a capacitor is used as main storage energy. Thus continuous input current can be obtained. Hence they have high efficiency and low switching losses.

For battery charging systems SEPIC may be preferred because of having;blocking diode which protects an unfavorable current from battery to PV. High ripple current output is also a disadvantage due to same diode. Hence a improved output current features can be provided due to the presence of inductor outside side. Thus a Cuk converter will be choosed for obtaining the fine input & output current uniqueness.

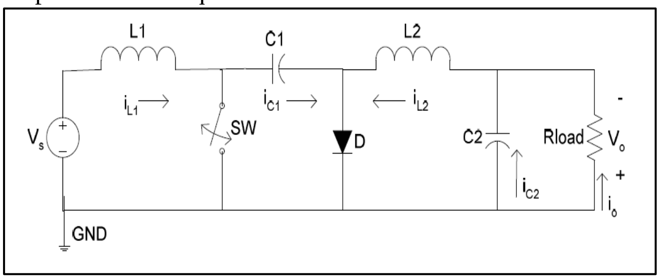

Fig. 5: Basic Cuk Converter circuit

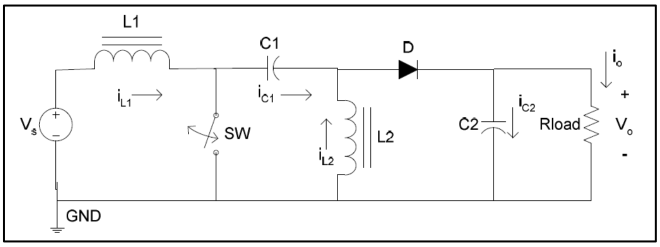

Fig. 6: Basic SEPIC Converter circuit

D. Operation of Cuk Converter

Continuous conduction working mode of a Cuk converter is examined here. Thus in this circuit, the average inductor voltage will be zero as it is in steady state. Thus by applying KVL for outer loop of circuit as showed in below figure.

$$V_{c1} = V_s + V_o$$

Switch (SW) is off and input voltage is turned on during initial condition. The capacitor (C1) is being charged and diode (D) is forward biased. Thus circuit operation can be categorized in to two modes.

Mode 1: When circuit switch SW turns on:

The capacitor voltage (C_1) which makes the reverse-biased of the diode and turned off. Thus energy of capacitor C_1 discharges to the load through the loop formed with SW, C_2, R_{load} and L_2. As inductors being enough large, as assuming that their currents are ripple free. Hence below equation is established.

$$-I_{c1} = I_{L2}$$

Mode 2: When circuit switch SW turns off:

By the input voltage (V_s), the capacitor (C_1) is being charged through the inductor (L_1). Thus stored inductor (L_2) energy is transferred to the load through the loop formed by D, (C_2), and R_{load}. Hence below equation established.

$$I_{c1} = I_{L1}$$

The average current is zero for periodic operation. Thus considering above equation and obtaining equation of duty cycle:

$$-I_{c1} = I_{L2}$$

$$[I_{c1}|SW_{ON}].DT + [I_{c1}|SW_{OFF}].(1-D)T = 0$$

$$-I_{L2}.DT + I_{L2}.(1-D)T = 0$$

$$\frac{I_{L1}}{I_{L2}} = \frac{D}{1-D}$$

Where: duty cycle (D) (0 < D < 1), and T defines the switching period.

Thus assuming it as an ideal converter, the power average absorbed by load must be same as average power supplied by the load.

$$P_{out} = P_{in}$$

$$V_0 I_{L2} = V_s I_{L1}$$

$$\frac{V_0}{V_s} = \frac{I_{L1}}{I_{L2}}$$

Hence

$$\frac{V_0}{V_s} = \frac{D}{1-D}$$

Thus duty cycle (D) relationship states that:

- If 0 < D < 0.5 output is smaller or lesser than input.
- If D = 0.5 output is equal or same as input.
- If 0.5 < D < 1 output is greater or larger than input.

IV. SIMULATION MODEL

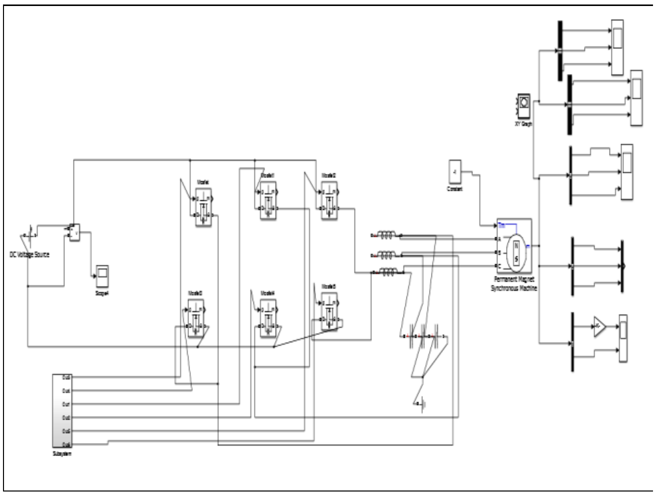

Fig. 7: Simulink Model of Proposed system

V. SIMULATION RESULTS

A PV array with the specification which is taken as an example of 305Wp module. Totally 8 modules of this 305Wp are arranged in series configuration of giving an array output of around 2400W, which will be varied based on environmental conditions of temperature and irradiance. For the reference solar intensity of 1000 W/m2 and 25^{0} C, the operating voltage Vmp and current Imp at the MPPT will be 37.5*8 V=300 V, and 8.15 A=96A, respectively as which modules are placed in series. The expected maximum output power at this operating point from this PV array is 2.4 kW (300V×8.15 A). Thus the array output around 2.4kW input power is fed to inverter or controller. As usual one can expect the output from inverters to be around 90% of its input power. Thus controller efficiently converts input to output with an efficiency of 90%. Thus motor will be fed with the power input around 2.2kW. Most importantly inverter output voltage is matched with the motor input voltage, so that high voltage may burn the windings and damage of motor occurs. Hence once motor gets sufficient voltage and power it runs with the maximum speed and giving a better output at the required height. Stages of the motor also play a role to operate at better height. Thus through simulation the speed and torque of the motor is observed well and which will be compared with the practically tested setup. The design on PV side and motor inverter voltage matching is also a key point in optimizing the design of Solar Photovoltaic Water Pumping System.

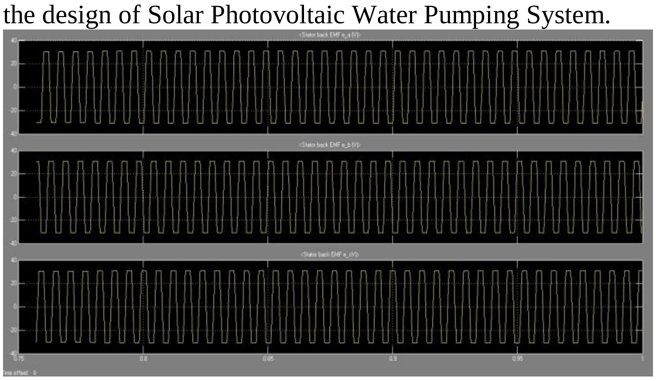

Fig. 8: Simulated waveforms of the proposed scheme of Motor back emf

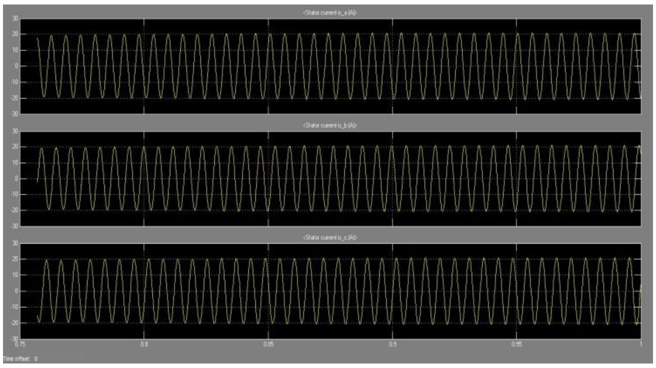

Fig. 9: Simulated waveforms of the proposed scheme of Stator current

The Power generated by solar is fully variable and depends on many factors like tilting angle, real temperature and instant irradiance to generate power. As once the PV output power is given to inverter and as the motor is loaded the output voltage of inverter jumps from open circuit Voc to actual voltage Vmp. Thus motor starts rotating and reaches its maximum speed. Hence as per simulation results this runs with a maximum speed of 1280rpm, as shown in figure below.

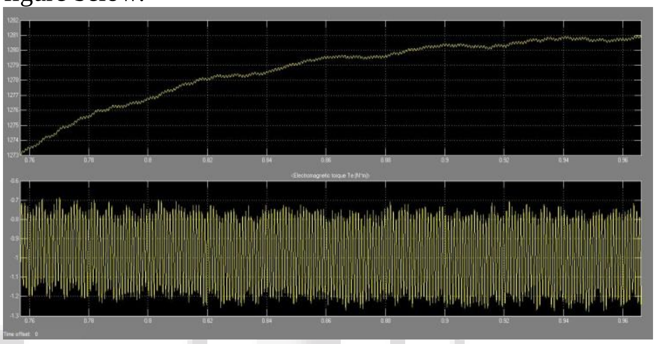

Fig. 10: Simulated waveforms of the proposed scheme of Speed and Electromagnetic torque

Hence in the actual real world weather condition the generation of power is varying too, thus it is very difficult to maintain the maximum speed of motor constant and to obtain good water discharge. Thus MPPT plays a key role for these interruptions, which can make the PV power output constant to the inverter input. So that maximum discharge is achieved with proper operation of motor. Thus this MPPT circuitry involves different algorithms on operation. P & O and IncConductane is the mostly used algorithms.

A. *Incremental Conductance Method*

This technique was proposed by Hussein in 1996 and mainly depends on change or derivative dependent of the PV-array with respect to the voltage at output is zero (dP/dV=0) at MPP during any temperature level & any irradiance level. The main aspect and idea is on curve of P-V slope at MPP will become zero. Thus by looking at slope it is easier in finding relative position of operating point. The following relationships below, shows the operating point on left and right of MPP.

At MPP: $0 = dP/dV$e

At left of MPP: $dP/dV > 0$e

At right of MPP: $dP/dV < 0$e

Hence the above equation becomes:

$$\frac{\mathrm{e}d(IV)}{dV} = \frac{dP}{dV} = I + V\frac{dI}{dV} = I + V\frac{\Delta I}{\Delta V}$$

At MPP: $\Delta I/\Delta V$ = -I/Ve
At left of MPP: $\Delta I/\Delta V$> -I/Ve
At right of MPP: $\Delta I/\Delta V$< -I/Ve

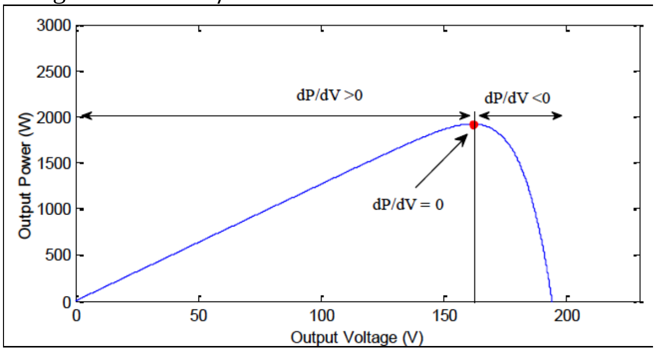

Fig. 11: Power derivative with respect to voltage

Once instantaneous and incremental conductance (I/V) becomes equal ($\Delta I/\Delta V$), operating point will be reached to MPP. Thus after reaching the MPP once, the PV array continuously stay at that point until there is some changes in ΔI is been calculated. Hence change in ΔI is affected or related with the atmospheric changing condition & MPP. To track MPP, the operating voltage is been incremented or decremented by algorithm. The algorithm is operating on the right side of MPP at the condition ($\Delta I/\Delta V$< -I/V) thus, to move the operating voltage towards MPP, operating voltage will be decreased. Similarly the algorithm is operating on left side of MPP at the condition (ΔI/ΔV > -I/V) thus, to move the operating voltage towards MPP, operating voltage will be increased. And once the MPP reaches the operating voltage ($\Delta I/\Delta V$ = -I/V), need not to change the operating voltage further. During steady state conditions, technique has an advantage of no oscillation around MPP and performs erratically on transient conditions.

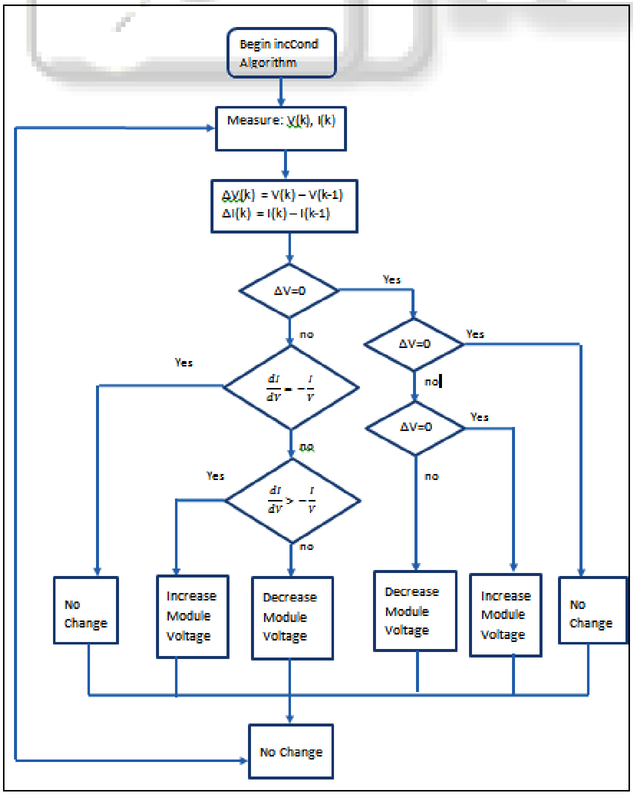

Fig. 12: Flow chart for inc Conductance Algorithm

VI. Conclusion

This paper presented the modeling and simulation in MATLAB of each and every component of PV systems provides the practicability of system in genuine conditions of weather. For designing solar powered Water pumping system of essential ability, the designed model of MATLAB can be used as a template. The results with a reasonable range are obtained by using the simulation model of DC water pump. The model accuracy is just uncertain and approximate because it is just a estimation of parameters in simulation. The results obtained and observed are satisfactory and promising. While comparing with the other system, it is well noted that Dc pumping system is more economical than AC. The discharge flow rate and efficiency of DC system is better more than AC system.

The technical factors evaluated for each installation will include the well and pumping characteristics, the solar radiation availability at the site, and the array configuration. For designing a most effective system of water pumping, designer must understand the well, the site terrain, the water requirements, and the storage system details. An understanding of the well requires information regarding the casing diameter, the static and the dynamic water depths. These parameters are used t calculate pumping time, pump size, and power demand on the pump which are in turn used to determine the load current from which the PV system size can be calculated. Mainly the Inverter DC to AC conversion also plays a major role. But for DC motors efficiency will be high in Solar Pump Controllers because of output PWM. Thus performance analysis on the actual system and its behavior, comparison and observations with simulation leads to optimization of the Solar Photovoltaic water pumping system.

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