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PHOTOVOLTAIC PUMPING SYSTEMS TECHNOLOGIES TRENDS

Dr. A. MOUSSI [(1)], A. SAADI, A. BETKA, G.M. ASHER [(2)]
[(1)]Research Laboratory in Subterranean and Surface Hydraulics (Larhyss)
University of Biskra, Algeria, info@larhyss.net
[(2)] School of Electrical Engineering, University of Nottingham, UK.

INTRODUCTION

Recent global developments appear to guarantee a market for green renewable energy. Among several sources of renewable energy currently explored, photovoltaic systems appear to be promising in view of their environmentally clean nature and the advantage of direct conversion to electrical energy. Of course, the sun is the original primary source of most of the other renewable energy resources: wind, wave, hydroelectric, biomass, geothermal...etc. The sun already provides almost all the energy needed to support life as we know it. On average, the earth receives about $1.2x10^{17}$W of solar power. The challenge for a sustainable future is to tap a tiny fraction of this energy to supply the relative modest demands of human activities [1-4].
Bell Laboratories were the pioneer of the first efficient solar cell, which was reported in 1954, attracted newspapers front-page headings. The New York times reported on the front page `` *Vast power of the sun is tapped by battery using sand ingredient*`` [1-3]. Since that time, much effort has been expended to make this statement true, even if it was grandiose at the time. The increasing use of these solar cells is linked to economic, efficiency and reliability factors and recent advances in solid state technologies has given a boost to the attractiveness of solar cells with high efficiency solar cells now available. Although the price is still high in comparison with other renewable energy resources, solar cells have advantages in terms of long-term reliability, maintenance, and minimal environmental and social impact. Photovoltaic module production has thus risen steadily since the seventies (a decade of the energy crisis), and has exceeded 24MW by the end of the last century. Solar electricity is becoming a fact in the world.

Isolated regions, where connection to the utility grid is highly expensive if not technically unaffordable, have found in solar electricity an excellent solution to their needs. In developed countries, it has become another alternative energy source and is seeing application in residential electrification, refrigeration and air conditioning solar electricity as well as small food industries, agriculture and health services [45-50]. In some cases, where the generated power exceeds the demand, electricity is sent into the grid. This requires new regulations and standards to be formulated.

Nowadays, the prime installation price of solar cells is still high (with the absence of governmental support in most countries), therefore, one has to properly size and optimise the system operation. Much research work concentrates on the optimal use of photovoltaic generator units which constitute 60-80% of the system price depending on whether storage means are used or not. The PV systems can be operated as a stand-alone, hybrid or grid connected systems. Stand-alone schemes have found wide application in remote regions to meet small, but essential electric power requirement such as water pumping systems. Research work has also emphasised this aspect [5-8].

Early studies focussed on ways of sizing, matching and adapting PV pumping systems since a proper match between the installed capacity with the isolated load is essential in optimising such installations [42-44]. Various works were done on the choice of the drive system to interface to the PV source, type of pumps to use and ways to control and optimise the whole system.

PV PUMPING SYSTEM ELEMENTS

A typical PV pumping system consists of a photovoltaic (PV) cell array, a power conditioner and the load, Fig.1. Of course, other accessories such as energy storage, cabling, transducers and protection are also needed. The power conditioning stage consists of a power converter associated with a suitable control unit. The load, for a pumping system, consists of a motor and a pump.

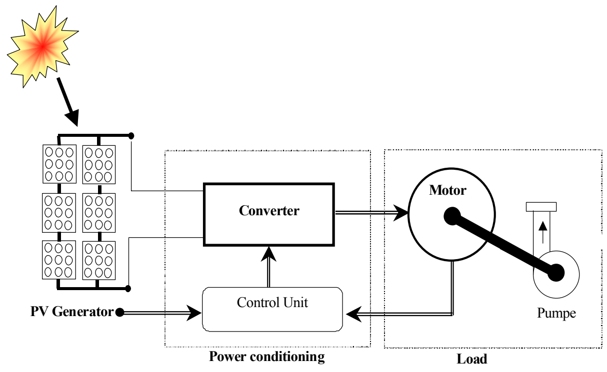


Figure1: Schematics of a photovoltaic pumping system

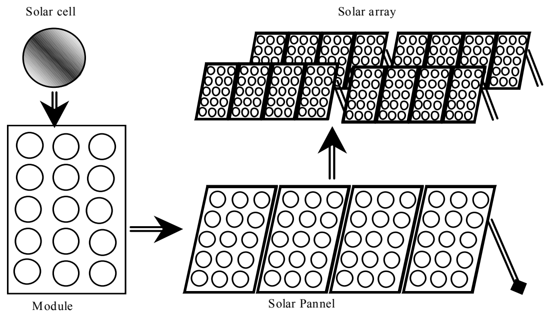


Figure 2 : PV generator hierarchy

THE PHOTOVOLTAIC CELL ARRAY

The fundamental power conversion unit of a PV system is the 'solar cell'. For practical use, they are usually assembled into modules. About 36 cells are typically interconnected in series in order to give a charging voltage for a 12V battery. For high power requirement, the modules are interconnected in series/parallel to form a DC power producing unit array known as generator, Fig.2.

The main characteristics which characterise a PV generator are shown in Fig.3 and it is clearly seen that the I-V output characteristic of a PV module is highly non-linear. It behaves as current source for the low voltage zone and as a voltage source in the high voltage zone. The output power in theses regions is far below the optimal values which could be generated if the solar array works around the knee of the I-V characteristic. The characterising rated values of an array are the short circuit current, open circuit voltage and maximum power as a function of temperature and irradiance. Typical characteristics are shown in Fig.3:a-d for a two parallel-ten series PV module.
Most authors give I-V and P-V characteristics as a function of solar insolation for a given temperature. However, the I-V and P-V characteristics are very temperature dependant. A fixed temperature doesn't exist in practice because of the heating effect of the radiated energy. This, when combined with the cooling effect of the surrounding winds, gives poorly predictable working conditions and makes the system difficult to model.

POWER CONDITIONING STAGE

a) Power Converter

The PV power sources are, by nature, non-linear. They are subject to large variation under environmental factors, mainly the irradiation and cell temperature, which in turn change the maximum power operating point. In order to speed up the amortisation of the system cost, it is essential to operate the PV generator at its maximum power point on a continuous basis. Therefore power-conditioning units are used for this purpose.
This unit depends on the type of load being feed by the PV generator. For a pumping system, the load is generally a DC or AC motor. For the former, the power-conditioning unit is most commonly a DC/DC chopper. Many types are used such as buck, boost and buck-boost [38-39].
Recent research has dealt with most of theses converters in order to find the most compatible type in terms of overall power system efficiency [30, 34-36]. It is stated that the boost converter is the most convenient for maximum power tracking [30-38]. Furthermore, if the required output voltage is less than the generated one, it is recommended to use a two stage conversion unit, the boos+step down converter [40].

If an AC motor is used, an inverter should be included in order to perform the DC/AC conversion stage. This has been reported in [20-23] using a six steps quasi-square wave inverter. Of course a PWM inverter yields better waveforms at no real increase in cost. Recently, resonant inverters have received attention [35,51,52] in order to reduce power losses at the inverter level and hence increase the net system power capture.
In most of the literature, power losses in the converter are neglected or averaged at some fixed value. This might be inaccurate since the applied current and voltage depends on the operating point and solar insolation.

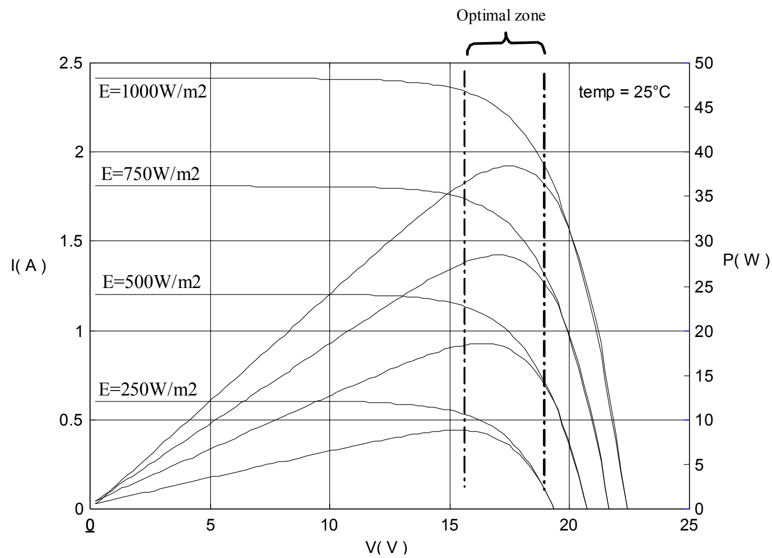


Figure 3 : Photovoltaic module characteristics

b) Control Unit

The main objective of this unit is to optimise the PV generator output power. For a given insolation level and temperature, the PV generator is characterised by the maximum power which can be delivered under a specific load current and voltage. This is known as the optimal value and one should force the PV generator to work under this condition. However, the operating point of the system depends on the characteristics of solar generator, the load and of course the climate and thermal parameters.

The simplest way to achieve a PV pumping system is to perform a direct coupling of the load, the motor-pump, to the PV source [11-16]. However, even if the size of the PV generator is initially optimised, it is shown that the efficiency varies broadly on temperature, insolation and drive parameters if these are varying. Fig.5 shows the operating point displacement of a DC motor-

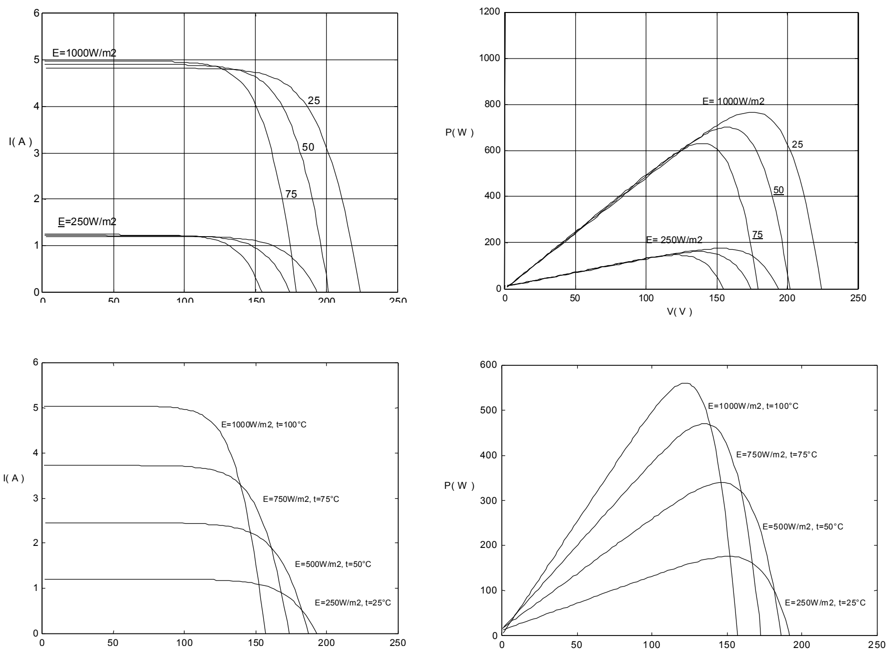


Figure 4 : Photovoltaic generator characteristics as a function of:
- a-b: Solar insolation (250-1000 W/m^2) and temperature (25,50 and 75° C)-
c-d: Solar insolation and temperature simultaneously

Centrifugal pump PV pumping system. Different pumps are considered for different levels of solar insolation and fixed temperature. The maximum power, optimal current and voltage are also shown. It is seen that, depending on the load I-V characteristic, a directly connected motor-PV system with a given load characteristic can be naturally optimised at the intersection point of the load characteristic and maximum power locus. This occurs for one value of insolation. As the insolation varies, the system becomes sub-optimal.

In addition, if the temperature changes largely, the optimised region will be lost thereafter. Fig.6 shows the pumps flowrates for direct coupling and for optimised power. It is clearly seen that the performance of the pumping system are improved if the output power of the photovoltaic generator is optimal.
In order to optimise the output power, in other words, track the maximum power of the PV generator, various techniques are used; these are called Maximum Power Point Trackers or MPPT techniques. These techniques are divided in two sets [32]: fixed voltage and true maximum power point trucking or MPPT.

- ***Fixed voltage control:***

From Fig.3, it can be seen that the optimal power can be achieved in a narrow zone of the output voltage. Therefore, if the output voltage is kept at a predetermined value, a sub-optimal power tracking can be achieved. A reference voltage is used in a control loop in order to drive the DC/DC converter such that $V_g=V_{ref}$.
Practically, there are two ways to implement this technique which differ in the way the reference voltage is handled:
a) The reference voltage can be a constant predetermined value derived from observing the PV generator characteristic and choosing a single value thereafter. This method is also known as constant voltage control without temperature compensation. In practice this value is chosen around 62-80% of the open circuit voltage V_{goc} measured for a temperature of 25°C and solar insolation of $E=1000W/m^2$, Fig.7

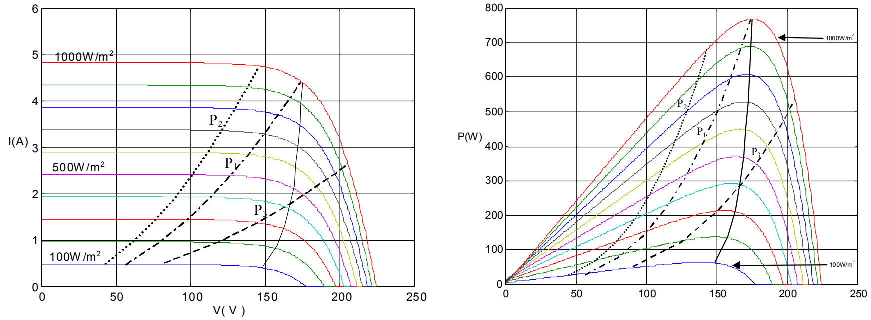
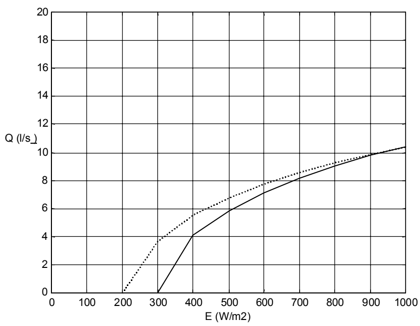
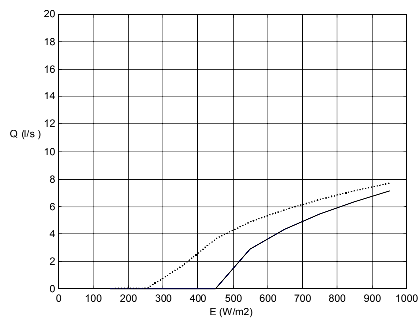


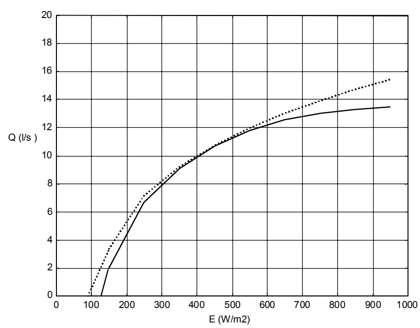
Figure 5: I-V and P-V characteristics of a PV pumping system, T=25°C
a) I-V characteristics b) P-V characteristics
Load Characteristics — Maximum power locus



Pump 1



Pump 2



Pump 3

Figure 6: Pumps flow rate as a function of solar insolation

.... MPPT —— Direct coupling

b) Knowing the relationship between the open circuit voltage V_{oc} and temperature of a PV module, the value of the reference voltage $V_{ref,}$ can be set a fraction of V_{oc}. The voltage V_{oc} is supplied in practice by a separate PV panel dedicated to this purpose. Alternatively the PV output may be periodically interrupted and V_{oc} quickly measured. Generally V_{ref} is chosen in the range 68-77% of V_{oc}., Fig.8. The first method has obvious limitations and has been practically abandoned. The second one offers sub-optimal results, but it is very easy to implemented and is price competitive.

This has made it a very popular technique and is widely used in medium power stations. Fig.9 shows comparative results of system efficiency for both previous techniques compared to ideal MMPT. It is clearly seen that the fixed voltage with temperature compensation, if properly designed and the system initially well matched, could be a serious competitor to the true MPPT.

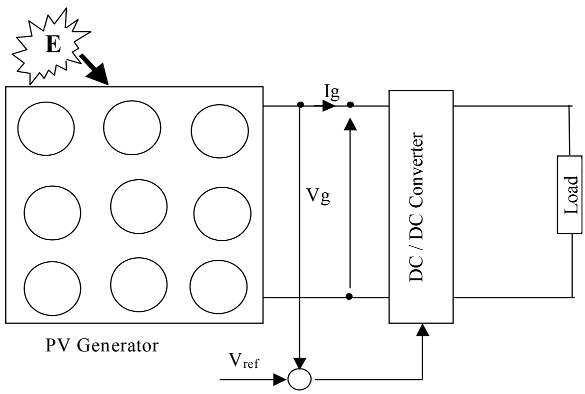


Figure 7 : MPPT without temperature compensation

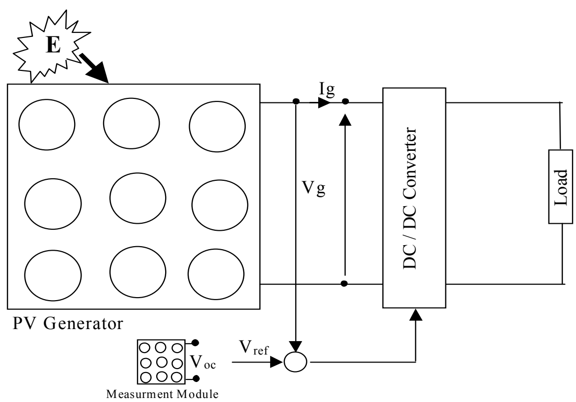


Figure 8 : MPPT with temperature compensation

- ***True Maximum Power Tracker:***

As the power drawn from a PV generator depends on the insolation, temperature and array voltage, it is necessary to match the load and PV generator in order to maximize the output power. Several ways have been tried out in order to seek the maximum power point of the P-V characteristic [13-27], Fig.7. The ideal way is to calculate the output power and compare it with the ideal one. The system is then pushed toward the optimal operating point. This method is tedious, complex and time consuming especially difficulties presented to find the ideal maximum power. The accuracy is affected for low insolation levels because the integration becomes more difficult and prone to errors.
One possibility is to exploit perturbation and observation techniques [46], known as well as hill climbing method, in which the operating point is moved toward the maximum power by perturbing the system periodically by increasing or decreasing the array voltage [28-31,34,36]. If a given perturbation leads to an increase (decrease) in array power, the subsequent perturbation is made in the same (opposite) direction. Hence, the MPPT hunts continuously the peak power operating condition. Its simplicity reside in the use of the output power only. But it present some disadvantages such as power fluctuation if the increment is large and non sensitivity for quick changes of solar insolation. The power fluctuation can result in a self-excited oscillation leading to an unstable system.

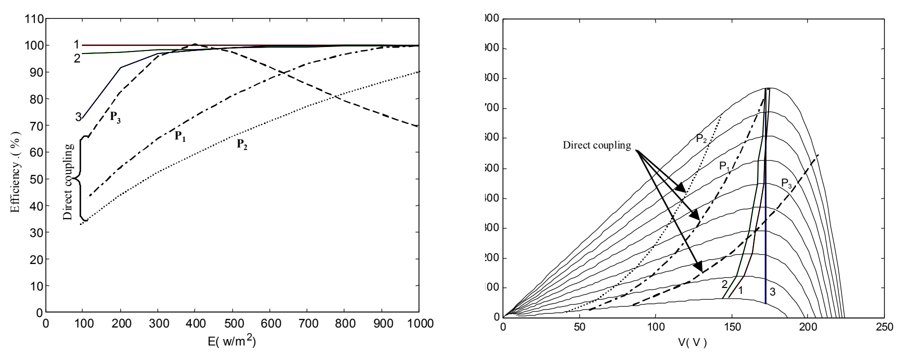


Figure 9 : System power efficiency as a function of solar insolation
1: True MPPT 2: $V_{ref} = \%V_{co}$ 3: V_{ref} = Cte
P_1, P_2, P_3 : Direct Coupling

Since the PV power sources are, by nature, non-linear. They are subject to large variation under environmental factors, mainly the irradiation and cell temperature. In addition they are generally connected to various load types such as energy storage system, fuel cells and even the distribution mains. Therefore designing systematically an MPPT controller is not always an easy task. Thus, modern control approaches, such as Fuzzy Logic, Neural Network and robust control have been suggested for fulfilling the function of tracking the maximum power point of a PV system. [27-28-37]

M. Goday [27] presented the analysis modeling and implementation of a fuzzy logic controller In order to search the maximum power of a PV array. The search is based on fuzzy heuristic rules which claims not to need any parameter information. Thus, no transducers were used in this application. However, different rule weights are used to cover different conditions corresponding to various sets of rules such as MPPT rules, temperature and insolation power dependency rules, and stabilisation rules. The author reported some advantages presented by this technique such as fast convergence, robust performances against parameter variation and can admit noisy and inaccurate signals.

Tsai-Fu Wu [28] has proposed a fuzzy logic controlled lightning system with battery backup powered by a solar cell generator. Design of appropriate controller was hard due to modeling difficulties of the system. Therefore, a fuzzy logic controller was suggested to control the battery charge/discharge and maximum power point tracking of the PV generator using a perturb and observe algorithm. Linguistic rules for the maximum power point tracking an battery charge/discharge were constructed and translated into fuzzy control rules.

Theses are collected by the fuzzy rule algorithm and used to control the system to meet the desired performances after the defuzzification process. The implementation was achieved on a single –chip microprocessor. The simulated and experimental results showed the robustness and adaptivity of the proposed FLC even though the system parameters variation.

T. Senjyu, proposed an extension method of hill climbing MPPT method reported previously using a fuzzy controller to increment of the duty cycle of the power conditioning converter. The information of maximum power point and insolation dependency were converted into fuzzy rules. The disadvantages encountered with the hill climbing method, which consists mainly in the conflict between rapidity and power fluctuation where avoided. The tracking time is shorter and the power oscillation is much smaller.

Artificial neural networks ANN have been reported by other authors. An ANN based real- time maximum power tracking controller for a PV grid connected system was reported in [24-26] and is shown in Fig.10. Reference [24] presents the application of an ANN for the identification of the optimal operating point of a PV module and involves measuring the actual PV output power and estimating the optimal power. The actual value is the product of the actual output current I_g and voltage V_g. However, in order to estimate the optimal power, the open circuit voltage V_{oc} and short circuit current I_{sc} are measured through monitoring cells and mapped to the optimal inverter voltage which is fed to switching control of the inverter. According to the results, it was found that there is a linear correlation between the short circuit current and the optimal current. However, a non-linear identification is necessary to get the optimal voltage from the measured value of the open circuit voltage V_{oc}. An ANN is therefore used for this estimation purpose, Fig.11. A three layer feed forward neural network was used with an off line training process to determine the connections weights.

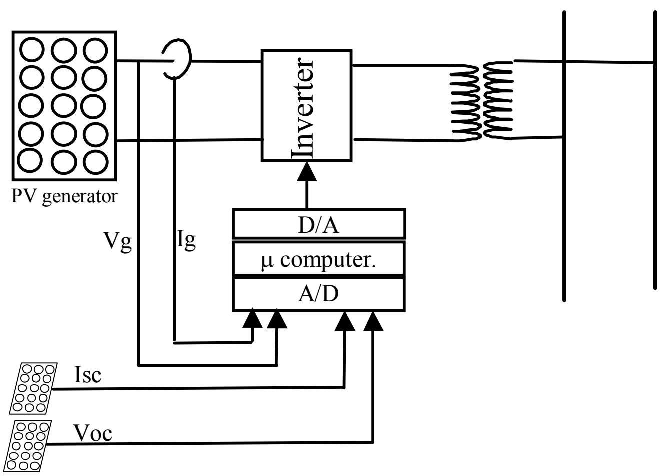


Figure 10 : Grid connected PV system

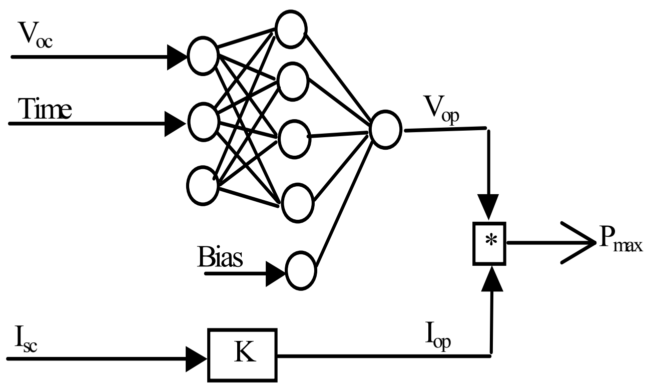


Figure 11 : Configuration of Neural Network

In another publication, the same authors used only V_g and V_{oc} for maximum power tracking [25]. The ANN was trained to identify the optimal operating voltage from the open circuit voltage Voc, Fig.12, which, in conjunction with the measured I-V characteristics, gives the expected maximum power. The system efficiency was only tested on a simulation basis. Nevertheless, the system would appear to present a poor response if temperature varies largely away from the measured data used in the training test.

In a his third publication, a long term ANN evaluation controller was implemented using solar insolation, temperature and wind velocity, which are measured directly, as inputs [26]. This is shown in Fig.13. The training is off line using several experimental training data sets. It was found that it is necessary to select training data with wide variations of the solar insolation and temperature. Results showed the robustness of the proposed ANN tracker and the efficient energy utilisation. The author reported that the proposed ANN can be utilised for prediction of the next day's generation by using the information from weather forecast bureau's. However, as the system is implemented, If only MPPT is required, similar results could have been obtained using simpler ways of optimisation such as look up tables or adaptive controller.

An alternative ANN based peak-power tracking for PV system using a DC Motor was proposed in [23] which is shown in Fig.14. In this scheme, on-line training is adapted using a reference pattern for the maximum power (MP) or alternatively gross mechanical power (GMP) derived from mathematical models.

A gradient descent algorithm is also used to improve the ANN power point tracking by changing the weights terms. Based on mathematical models, the chopping ratios of the power converter were computed at different solar insolation and compared with the predicted values. The results were closely matching even though the system was trained for ten solar insolation levels. Since the only input required was the solar insolation, the system will be indifferent to temperature changes.

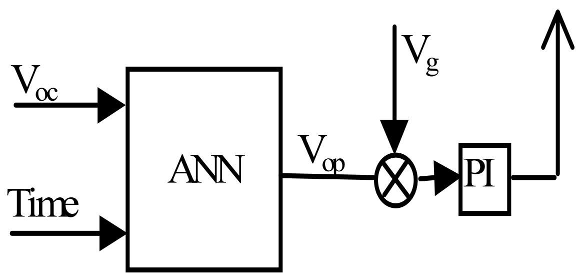


Figure 12 : Block diagram for optimal voltage identification

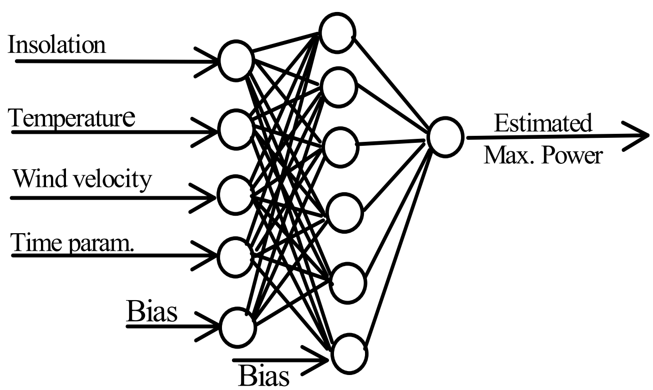


Figure 13 : Long term ANN maximum power optimisation

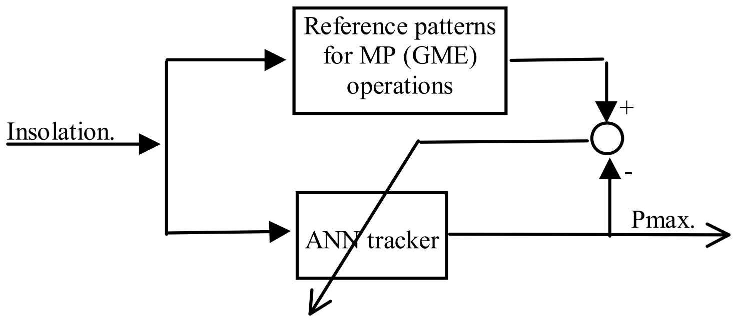


Figure 14 : Block diagram for ANN training

For all these researches, a three layer ANN is used since it has been proven that a network with one hidden layer is sufficient to approximate any non-linear continuous function [56]. The input layer can have many inputs depending on system complexity , The output layer has only one node which is used to adjust the power converter (DC/DC or DC/AC) control signal. Robustness of the proposed ANN trackers depends on the training data sets, their versatility and inputs of the ANN. The on line training scheme is more advantageous than the off line since the weight parameters can be adjusted adaptively.
One can optimise either the net mechanical output power [13,18,19] or the motor efficiency [17,22]. It is shown that the PV-load operating points for both schemes don't coeincide [11-13]. In addition, optimising motor efficiency diminishes the PV generator efficiency

LOAD

a) Motor.

Initially, pumps were driven by DC motors. Direct PV generator-motor coupling where the motor has been of series, shunt, and separately excited DC type have been considered together with their respective steady state and transient performances [11-15]. The system performance is very different to those obtained when these motors are connected to a constant voltage source. In addition it was found that the starting time is larger when any type of DC machines is connected to a PV source [12].

In addition the system starts to rotate only at high insolation level for constant loads characteristics. For an aerodynamic load characteristic (centrifugal pump), the system requires a relatively lower static torque and the system starts to rotate at lower insolation level.
Therefore, for high static loads, the system may stay at standstill until the solar insolation is sufficiently high to develop the required torque for starting. In [12,13] it was concluded that the separately excited DC motor was the more suitable for PV systems since it offers the best matching with the PV source. The inclusion of an MPPT improves the starting and steady state performances of the system [15-20]. Transient characteristics of a DC motor powered by a PV generator were considered [14,17,19]. Starting to rated current and torque ratios were investigated for system with and without MPPT. The starting current magnification, defined as the actual to rated value, for several DC motors types were found to be almost the same and were in the allowable limits. However, the starting torque magnification for the series and separately excited motors was too high for the drive system at high insolation level. In this case, the MPPT may be controlled to operate off the maximum power point to meet the desired torque at starting. In steady state operation the MPP is tracked for a maximum utilisation of the available power of the PV generator [17].
These studies were important since the highly non-linear source impedance of the PV generator causes a very different performance (under load) to the case when the machine is driven from a constant voltage source.
Due to maintenance problems encountered with DC motor drives, AC motors offered an attractive alternative where reliability and maintenance free operation are important such in pumping systems. This was emphasised by the decreasing cost of highly effective solid sate devices and control systems. The load matching of an induction motor-PV pumping system was investigated in [53]. A programmable PWM inverter feeding the induction motor was used. The PV generator is directly coupled to the inverter input. Simulation results shows that the utilisation of the PV array mainly depends on the solar radiation profile, the array power capability and the load characteristic. The matching factor, defined as the ratio of the actual array output used for water pumping to the array output capability, for the given load was found to vary between 0.74 and 055 (best and worst solar insolation seasonal variation situations respectively). A higher matching factor can be achieved by carefully selecting the proper sizes of the array and the motor-pump.

The introduction of an MPPT on an induction motor-PV pumping system is presented in [54]. It examines MPPT effect on PV generator efficiency when applicable to the V/f controlled induction motor driving a submersible pump. The loading of the PV generator without the MPPT was always low and below the system capabilities.

When the inverter with MPPT was used, the available PV power is utilised more efficiently. In this case, as the PV generator output voltage varies with respect to solar insolation variations, the inverter frequency is adjusted accordingly to meet the max power point operation.

Steady state and transient analysis of induction motor fed from a PV source were considered [20-22]. Alike DC motors, The induction motor characteristics were severely affected by the non linear characteristic of the PV source. PV maximum power tracker and optimal motor efficiency were studied in [21]. It was found that the motor steady state characteristics were limited by the switching frequency of the CSI and the chopping ration of the DC-DC converter. A voltage source induction motor-PV pumping system was reported in [22]. Two optimisation techniques were investigated: either the PV generator maximum power is tracked or the induction motor is controlled to generate the maximum efficiency. In the latter case, the unique speed of operation corresponding to this mode, limits the value of water discharge rate that could be obtained. In addition, it diminishes the solar utilisation period of the PV generator which operates efficiently only over a small range [22].

Developments in the field of electronic, control and materials technology have given impetus to new motor designs. Using high magnetic density PM motors based on rare-earth magnets (Samarium-Cobalt, Neodymium-Iron-Boron), high power/weight and torque/current ratios have been obtained. It is generally accepted that the high power density, high efficiency and fast dynamics of PM motors make them well suited for PV pumping [17,19,29] up to a few tens of kWs whereupon the cost advantages of the induction motor become significant.

b) Pump.

For PV pumping, two types of pumps are widely used: the volumetric pump and the centrifugal pump. With respect to their load characteristics, the volumetric pumps behave as a constant load whereas the centrifugal pump has an aerodynamic characteristic. It has been reported that the energy utilisation of the PV generator by the centrifugal pump is much higher than by the volumetric pump.

This is because the centrifugal pump works for longer periods even for low insolation levels and its load characteristic is well matched to the maximum power locus of the generator [9,10,12,21]. In [41] it was found that the efficiency of a directly coupled PV pumping system is 58.11% for a volumetric pump and is more than 86% if a centrifugal pump is used.
For small appliances, the vibratory pump can be used [35,51,52]. This type of pumps is characterised by its simplicity, low cost and robustness allowing long life use. The flow rate is controlled generally by varying the supply frequency. Therefore, in order to improve the system overall efficiency by reducing the inverter power losses, resonant converter are usually used with this type of pumps.

DISCUSSION AND CONCLUSIONS

This paper has reviewed the principle research activity in photovoltaic pumping systems over the past decades. Prior to the common use of power converters, the principle problem was the to find the best matching of DC motors connected directly to the PV array and, naturally such systems were very sub-optimal in that they were unable to utilise the PV capacity. The use of power converters has allowed the extra freedom to exploit the maximum energy capture from the PV arrays. Much of the research focussed on control mechanisms to derive maximum capture (MPPT algorithms) in the presence of variable insolation and array temperature. These methods, ranging from simple constant voltage through to hunting and adaptive techniques have been discussed. Apart from the requirement of adaptability based on the temperature-dependent array characteristics, the MPPT algorithms represent an interesting control problem. This is because the power converter may be viewed as an impedance changer making possible an optimal (and adaptive) impedance matching between the array and the motor-pump load. The dynamics for the control design are then seen to be highly non-linear and represent a good application of fuzzy and neural network techniques. It is of interest to note that other control techniques, such as variable structure and model reference adaptive methods have yet to be applied. However, it may also be observed that the plant structural changes are relatively slow and that the low target bandwidths would tend to make the comparative advantages of various methods somewhat marginal.

Historically, research implementations have used DC-DC Converters and DC machines owing to their cheap and simple power electronics. The derived MPPT and adaptive algorithms however are applicable to other machine types also. These include the brushless PM machine which has the advantage of high power density and very high efficiency (at the expense of cost), and the robust and cheap cage induction machine. Both require DC-AC conversion, either interfaced to the PV array directly or, to achieve voltage matching, through a DC-DC step-up chopper.

Recent research has focussed on achieving the most energy efficient control algorithms for AC machine-pump loads in which MPPT tracking and maximum motor and pump efficiency are the system performance targets. Naturally, the system cost and the amortisation of these costs over the system life are important factors.

The paper has focussed on pumping systems since water pumping for agricultural use is a common application in remote areas having high insolation levels and the requirement of stand-alone power. The technologies contained in the review are of course applicable to air-conditioning and refrigeration applications as well as those demanding integrated hybrid power sources. In all cases, the design of PV-drive system and control requires a number of common questions to be answered:

What are the quantitative characteristics of the load? The load characteristics will often constrain the drive system to operate within a confined voltage-current envelope. This needs to be defined in order to arrive at control methodologies which are near optimum, reliable and cost effective. These will not necessarily be the most sophisticated. Similarly, the characteristics will have an impact on drive starting as well as fault protection strategies.

What are the base requirements for power losses and system integrity under loss of power source? This issue impacts on the size and rating of the PV arrays and the requirement for over-capacity (if any). In addition, the insolation may not be continuous and issues of load interruption and energy storage will effect both the system complexity, control management and cost.

What determines the choice of technology and system control? The type of power converter and drive is still an open issue and is dependent on reliability and cost, especially for applications in which simplicity may be an overriding issue; indeed there is still an argument for the direct connected DC motor-pump drive which can be understood and maintained with very little basic knowledge by a local population.

However, for sites in which communication and remoteness is less of a problem, it would appear that the AC drive solution with appropriate power conditioning will turn out to be the most best compromise between initial price, reliability and total energy delivery.
In terms of cost per kilowatt, PV arrays are still the most expensive of the renewable sources and are likely to remain so for the foreseeable future. The future penetration will of course be influenced by advances in PV device technology and the cost of these devices.
The cost of power conditioning and control is already a relatively small proportion of the system cost and it can be well argued that the main constraints on the take-up these drive technology units are those of reliability and availability of replacements rather than the control complexity. Upon this line of reasoning, the control and system methodologies described in this review would appear to have a good future.

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