Realistic Maximum-Power-Point Tracker for Direct Water Pump Systems using AC Motor Drives

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ABSTRACT: According to statistics of the World Health Organisation (WHO), 50% of the people in developing countries have no pure drinking water. PV-powered water pump systems can improve peoples living conditions, where power from an utility is not available or too expensive to install, especially in remote or rural areas.
Therefore, a system is designed and build up consisting of a PV array, a standard inverter, an induction motor and a water pump with a storage. The implemented PV array has a peak power of 1,2 kW. To search the maximum power point (MPP) of the PV array, the inverter is operated with variable frequency adapting the power input of the induction motor. The inverter is controlled by a development platform, based on a digital signal processor (DSP). This device generates a pulse width modulated (PWM) voltage output. The PWM is calculated by a program for MPP tracking control (MPPT), sine wave generation and a day-startup/night-shutdown automatism.
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1. Introduction

The system studied in this paper is a PV powered water pump system, consisting of a PV array, a low cost inverter, an induction motor and a water pump with a water storage (Fig. 1). The PV array has a peak power of 1,2 kW. The inverter operates as a variable frequency source (PWM) for the induction motor driving the pump. Furthermore, the inverter is equipped with a maximum power point tracker (MPPT) and a day-startup/night-shutdown automatism.

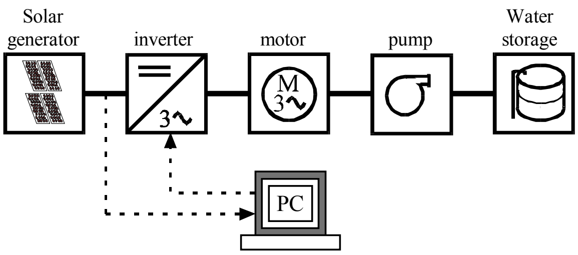

Figure 1: Block diagram of the analysed system.

Most PV powered water pump systems consist of two different control units. The first is a dc unit with or without battery as energy storage. In this unit, the MPPT is controlled by varying the duty ratio of a dc-dc converter. Using this converter leads to a less complicated control algorithm for the MPPT. Varying of the dc voltage can be done more quickly and without changing the power or frequency of the motor. The influence of a changing irradiance during a searching procedure is reduced. On the other hand, this converter introduces many losses, e.g.:

- switching losses
- valve losses
- copper and iron losses in the filter coil

In control systems without a battery, the dc bus may collapse when an unbalanced input/output power ratio occures at the dc bus. Systems without battery require a more complex control algorithm. The second control is for the dc-ac inverter to generate the sine wave of the induction motor.

The system analysed here is a water pumping system avoiding the use of the additional dc-dc converter, a battery and its losses. The power of the PV array must be used immediately to accelerate the induction motor, because of the lack of a storage in the dc bus.

As the irradiance increases, resulting in a higher output power of the PV array, the input power in the dc bus is higher than the output power. The MPP control must immediately accelerate the induction motor to track the MPP of the PV array.

With decreasing illumination the power of the PV array is smaller than the output power in the dc bus. This is the most critical condition of the system. The dc bus may collapse if this condition continues. Hence, the inverter must slow down the induction motor. Therefore, the controller should guarantee a balanced input/output power ratio in the dc bus.

To optimise the energy captured by the PV array, the output power should always be at its maximum. The output power of the induction motor can be controlled by varying the frequency of the sine wave, generated by the inverter. Consequently, the speed of the motor and the water pump changes.

All implemented MPPT's are realised by feeding back the dc voltage and the dc current to the controller, to adjust the frequency output of the inverter and keep the system operating at the maximum power point. The inverter is controlled by a digital signal processor (DSP) based developing platform realizing the MPPT's, sine wave generation and the start up and shut down automatism's. To ensure an overall low cost system the complete algorithm can be implemented in a simple microcontroller.

Several novel concepts of MPPT are developed, analysed and tested, because the MPPT algorithms described in literature [1]-[2] for this kind of systems turned out to malfunction, when tested under realistic conditions. The performance of these novel concepts of MPPT for PV-powered water pumping systems is evaluated. Advantages and disadvantages under realistic conditions are discussed.

2. PV ARRAY

The voltage-current characteristic of one PV element at constant cell temperature is shown in figure 2. The output power of the PV element is drawn in the same figure. The Maximum Power Point (MPP) is characterised by the voltage, where the PV array generates maximum output power. The practically studied PV array that has been built up consists of 11 modules in series with a total peak power of 1,2 kW.

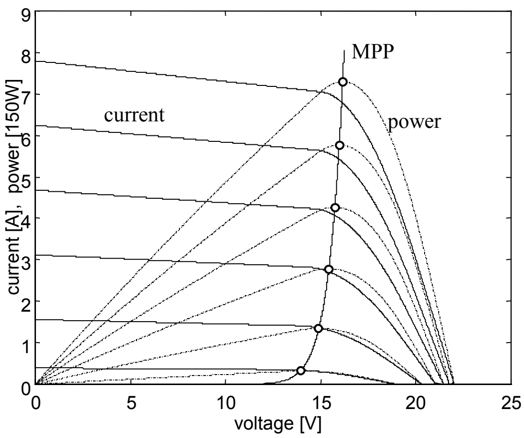

Figure 2: Characteristic of one PV element at constant cell temperature.

The characteristics of the PV elements are affected by the irradiance and the cell temperature. In figure 2, six different levels of irradiance are illustrated. With increasing irradiance, the MPP moves along the dotted line. In order to reach the point of maximum power at rising irradiance, the current in the dc bus must be increased, too, while the dc voltage remains nearly constant.

The voltage at the MPP changes with the array temperature and the current is almost unaffected. At lower cell temperature the MPP characteristic is situated in a higher voltage range. Thus, the optimum output voltage of the PV array is not constant and moves as the condition varies.

In contrast to the very fast and frequently changing irradiance, the cell temperature of the PV array and thus the dc voltage in the MPP varies very slowly. Therefore, MPPT should be performed by varying the dc voltage in a small range, searching the MPP and controlling the speed of the induction motor in order to guarantee the calculated optimum voltage.

3. DRIVE SYSTEM

The output power of the pump P_{out} at constant pipe characteristic is a function of the rotor speed ω_n :

$$P_{out} = k\,\omega_n^3 \qquad (1)$$

Increasing the frequency supplied to the motor driving the pump results in a higher output power of the system. Without energy storage in the dc bus, the changing power of the PV array must be adjusted by varying the frequency of a dc-ac inverter.

The high efficiently inverter generates the sine wave of the induction motor with asynchronous pulse width modulation (PWM) at a cycle frequency $f_c = 10$ kHz. The control and measurement units of the stand-alone inverter are also supplied by the PV array. These units require a power $P_s = 10.5$ W. The efficiency η_{inv} of the inverter at no load supply is shown in figure 3 as a function of the dc voltage. Without consideration of the no load supply the efficiency is above 97%.

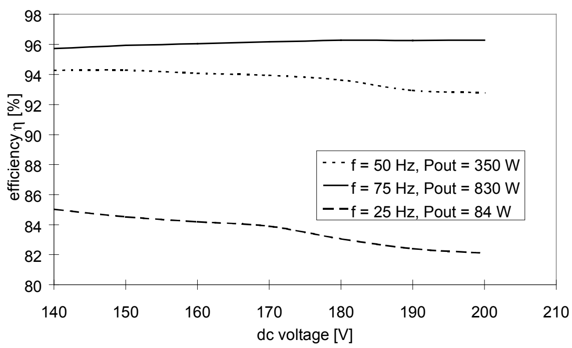

Figure 3: Efficiency of the dc-ac inverter.

The efficiency η_{inv} is normally given as a function of the current. Here, another form is presented, to show the dependence of the dc voltage. Due to the smaller gradient of this characteristic, compared to the gradient of the power around the MPP, the maximum speed of the water pump is reached at the maximum power point of the PV array. Otherwise, a deviation from the MPP would be necessary to get the highest motor speed and the tracking must be performed by using the frequency for the calculation of the optimum power-voltage point. Furthermore, the delay between frequency and voltage must be well known. The delays between frequency, motor speed and voltage are caused by the inertia of the motor, the capacitor of the dc bus, the used filter and the execution time of the control.

Thus, the power, calculated by measured dc-current and dc-voltage, is used for the MPP calculation. The advantage of this method is the fact, that there is no delay between the measured voltage and the measured power.

Adapting the frequency of the applied ac-voltage changes the speed of the motor. Keeping the stator flux of the induction motor constant results, for small slip frequencies, in a linear torque-speed characteristic.

Additionally, a third harmonic is injected in the output voltage of the inverter to enlarge the modulation range of the inverter and to minimise the nontriple harmonics in the current of the motor, which increases the current in one phase while it decreases in another. The influence of the injection on the 5th and 7th harmonic at a modulation index M = 1 and an output frequency f = 50 Hz is shown in figure 4. The modulation index used here is defined by:

$$M = \frac{\hat{u}_{reference}}{U_{dc}/2} \qquad (2)$$

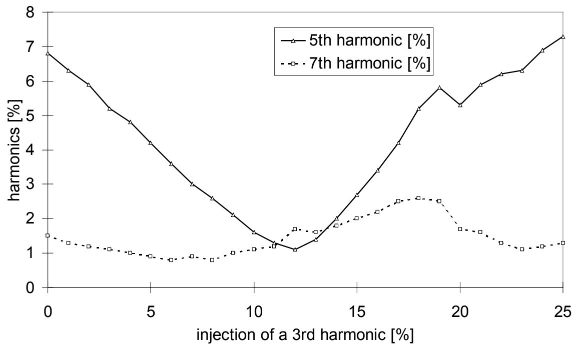

Figure 4: Injection of a third harmonic.
(Modulation index M = 1, frequency f = 50 Hz)

The injection of a third harmonic, which magnitude amounts to 12% of the fundamental, results in a 75% reduction of the 5th harmonic. The third harmonic has the same position in all three phases and is therefore not present in the output current.

4. MPP-Tracking

The efficiency of the output power of a PV array can be enlarged about 2% by MPP-Tracking, compared to a common constant voltage tracking.

The task of the MPPT is to calculate the frequency for the induction motor for keeping the PV array operating at its MPP. This control is realised by feeding back the dc voltage and current. With these input quantities the controller is able to calculate the output power of the PV array. A measurement of the output power of the PV array in the MPP is plotted in figure 5, being a typical function of the power for a cloudy day.

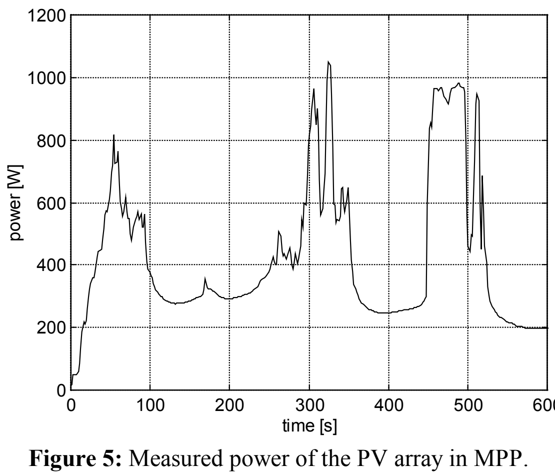

Figure 5: Measured power of the PV array in MPP.

4.1 Control approaches

The MPPT algorithms for this kind of systems, described in literature, can be divided in two main categories.

The first approach is based on a constant frequency for a short time [1]. To vary the output power of the PV array, the inverter frequency is varied in steps. This control algorithm permits only slow changes in the output power of the PV array. As shown in figure 5, the PV array changes its output power in the MPP very fast and frequently. With decreasing light intensity the power of the PV array is smaller compared to the output power in the dc bus. The difference between the input/output power ratio is compensated by the capacitor of the dc bus. This condition continues until the capacitor is discharged and the dc bus collapses, because slowing down the motor in steps takes too much time. Under realistic circumstances the systems based on this control algorithm collapses with a fast decreasing irradiance.

The second way to realise a MPPT is based on a constant voltage in the dc bus for a short time. As shown in figure 2, the dc voltage in the MPP is nearly independent of the light intensity. The cell temperature of the PV array and thus the dc voltage in the MPP varies very slowly. MPPT is performed by varying the dc voltage in a small range and calculating the new dc voltage with the measurements. Without additional dc-dc converter in the dc bus, the variation of the voltage must be slow to avoid instabilities of the induction motor. Therefore, this kind of system requires a more complex control algorithm.

The implemented MPPT, based on the second approach, will be explained and discussed in the next paragraph.

4.2 Inner control loop

The overall control of the MPPT consists of two cascaded controllers. The inner control loop varies the frequency of the induction motor to remain in the calculated optimum voltage range. The input of this inner control loop is the voltage error, calculated from the measured and filtered dc voltage and the reference voltage given by the main control loop. The error voltage of this inner control loop is presented in figure 6. It describes the same span of time as the MPPT in figure 5 in order to show the influence of the changing irradiance.

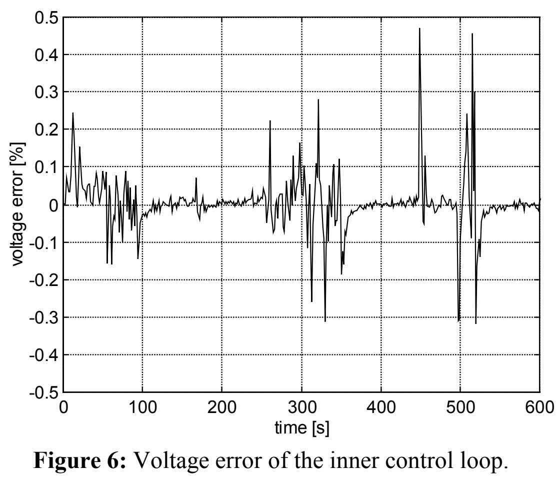

Figure 6: Voltage error of the inner control loop.

The averaged voltage error of the inner control loop is smaller than 0.1%. Also at the starting procedure and under very quickly changing irradiance the error reaches a maximum of 0.5%. The averaged voltage error delivers the minimum search range for the main control calculating the MPP. The inner control loop is done by a common PI controller with anti-windup. The parameters of this controller result from the transfer function of the dc voltage to the speed of the pump according to the symmetrical optimum. This transfer function depends on the delays of the voltage filter, the execution time of the control, the capacitor of the dc bus and the inertia of the drive.

4.3 Main control loop

The main control loop calculates the MPP and the search range of the dc voltage and delivers the reference quantity of the inner control loop.

The starting procedure of the MPPT is demonstrated in figure 7 showing the measured dc voltage over the same span of time as in figure 5 and 6.

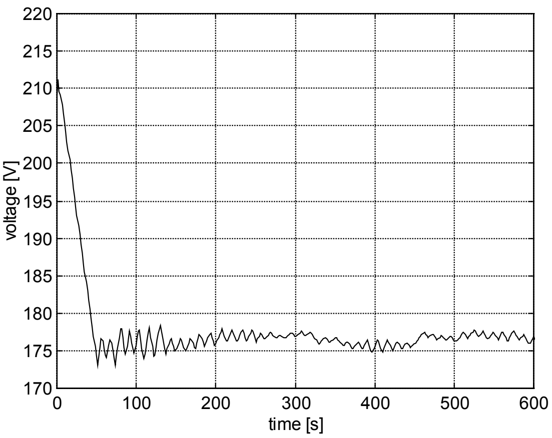

Figure 7: Starting procedure and MPPT.

First, a default voltage and search range must be given. After the default voltage is reached, the voltage will be varied around this point. The quantity of the variation is given by the search range. During this variation the power generated by the PV array is measured and the voltage linked with the maximum power is stored during the respective searching procedure. The new optimum voltage and the new search range are calculated from these measurements and the past with an adaptive controller. With these quantities the controller starts a new searching procedure to find the MPP.

The previous values are very important for the calculation of the new optimum voltage and search range. If, e.g., the new calculated optimum voltage during a searching procedure with rising voltage is situated higher than the past optimum voltage the MPP-voltage seems to change. But this can also indicate an increasing irradiance. If the second condition is given, the controller should not change the new optimum voltage. Otherwise, the calculated voltage drifts away from the MPP. The same considerations are also valid for a decreasing irradiance. Thus, the adaptive control must be able to distinguish between a changing MPP and changing conditions. The search range depends on the variation of the calculated optimum voltage. If the calculated MPP is situated in the half of the past voltage range, the search range is reduced, otherwise it is increased.

4.4 Experimental results

Measurements of the implemented MPPT are plotted in figure 8 showing the power of the PV array as a function of the dc voltage. Four different starting conditions (a-d) are shown to demonstrate the ability of reproduction of the MPPT. The characteristic c and d exhibit the MPPT starting with an unbalanced input/output power ratio on the dc bus. The MPP-voltage at characteristic a is situated in a higher voltage range, because it shows the first searching procedure at a lower array temperature.

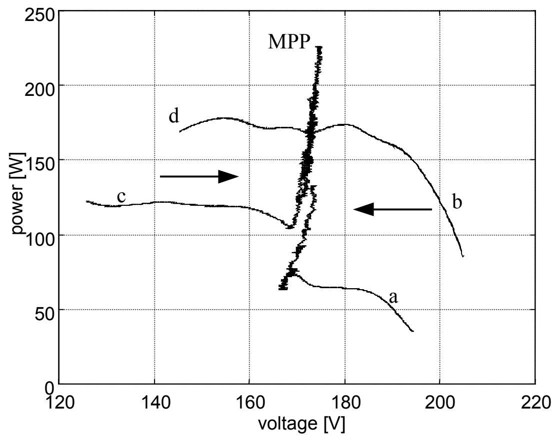

Figure 8: Measured results of MPPT (6 hours).

5. Conclusion

The system described is a PV water pump system using ac motor drives. Different MPPT controls without using an additional dc-dc converter are explained. All implemented MPPT's are realised by feeding back only the dc voltage and current to the controller, to adjust the frequency supply of the ac drive and keep the system operating at the MPP. The measured results of the MPPT exhibit the ability of reproduction and the stability of the system, also if the condition changes.

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