ECONOMICAL MPPT METHOD FOR PHOTOVOLTAIC SYSTEM WITH CHANGING OPERATING CONDITIONS

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The power of photovoltaic cells (PV) varies with illumination, temperature and radiation. The paper introduces a new matching method and a simple economical implementation for the DC-DC conversion applied at PV terminals. The method uses a "boost" configuration controlled only by trigger, flip-flop and analog circuits. It results minimal complexity and component number. An event detection method, changes the sense of the reference current variation only when the power derivative becomes negative. A repetitive initializing procedure eliminates the effect of changing environmental conditions. Simulation results are obtained for step variation of the PV device characteristics.

Keywords: MPPT procedure, photovoltaic cell, boost circuit, analog signal processing

1. Introduction

The maximum power point tracking (MPPT) problem arises when renewable sources are used. In the field of the PV applications different algorithms and methods are used, referred for example in [1] and [2]. The problems needed to be solved concern the nonlinear behavior of the PV devices, the type of control parameters, the type of power switching circuits, the choice of reference values and the maximization criteria. During time, analog and digital processing control strategies were developed, the latest being based on DSP processors and complex algorithms.

Regularly, the PV device is connected by a static converter to a battery (DC-DC link) or to grid (DC-AC link). In the first case, the transferred power is limited by the superior admissible voltage of the battery, but in the second, all the energy available from the PV devices may be transferred. A possible solution (Fig.1) is to use an intermediary capacitor between a DC-DC input converter having MPPT function and a DC-AC output converter controlling the sinusoidal current, injected to grid. This controls the current amplitude, in order to maintain an optimal value of capacitor voltage.

The paper presents an original working method and implementation for the MPPT input converter. The electrical parameters responsible for power maximization are

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the voltage and current at PV device terminals. The PV device characteristics have strong variations when radiations conditions are changed rapidly. Then, voltage changes are fast and the MPPT procedure may be perturbed. Different methods that overcome this effect are reported [3]. The presented method is based on a simple repetitive initialization technique, under realistic operation hypothesis. It may be classified as a differential time dependent power tracking method.

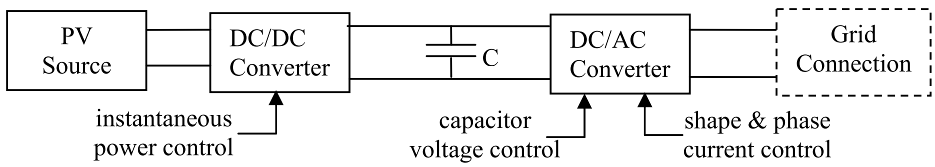

Fig. 1. General configuration for MPPT conversion

2. Operating principles and block diagram

The paper is focused on the design of the input DC-DC converter. Its output is connected to a storage capacitor. The purposed operation principle is described by a block diagram in Fig.2. For MPPT operation, the absorbed current value must lead to a maximum transferred power. For instance, consider a constant value for PV terminal voltage. In this approach, it is considered that the current has permanent linear variations with a fixed positive or a negative slope. At the initial state this may be arbitrary. During normal operation, the current slope is switched when the power becomes decreasing. Thus, an optimum may be achieved, progressively, by current variation in the direction of power maximization.

The control circuit is based on two stable operation states, determined by a flip-flop circuit. The current magnitude is tuned by a boost switching circuit. It is controlled feedback loop with a hysteresis operating mode. The reference current is a linear ramp generated by an analog integrator, having a positive or negative constant input, corresponding to the flip-flop state. In order to obtain bipolarity, the flip-flop output is offset by an adder operator with a negative level. The flip-flop is switched when a positive front occurs to input. This corresponds to a positive-to-negative transition of power derivative, considering the inverting action of trigger circuit (B). Thus, if the power increases, the sense of the current variation is maintained. If the power decreases, the sense of variation is changed. Always the power variations are directed toward the maximal value. Thus, this MPPT method is based only on absorbed current control.

However, the power evolution is determined both by current and voltage variations. In reality, the PV device voltage may have slow changes, due to the current variations on finite equivalent impedance or fast variations, due to certain environmental changing conditions. Strong voltage variations may change the power derivative sign, acting as a perturbation factor on the current control procedure. During the MPPT procedure, a descendent power variation is always followed by a change in the current variation. But, an ascendant power variation must be maintained, until the maximum is reached. Thus, a strong decreasing of voltage changes, in a wrong manner, the correct sense of current variation and the maximization procedure becomes divergent. In this case, in a rigorous approach, the maximization method must consider the voltage variations too. However, taking into account that the strong voltage variations, due to the environmental conditions, occur relatively rare and with very low frequency, a simple re-initialization procedure may be used in order to restore the correct procedure. For this, as long as the power derivative remains negative, an additional pulse generator forces changes on derivative signal, in a repeating manner. If the voltage becomes again stationary, the maximization procedure is again dependent on a single parameter and will operate normally. This strategy is necessary because this MPPT procedure is an event dependent one, changing the current slope only for descendent power transitions. If another factor, than the current, is the cause, the wrong sign slope remains unchanging and the process remains divergent.

In Fig. 2 two different control loops are used. The first (current loop) controls the boost current as a function of reference current I_R. The second (power loop) controls the sign of the reference current slope. The integrator output generates a linear ramp signal with positive or negative slope, depending on the sign of the input value. The current slope sign is changed by the flip-flop circuit when the power derivative signal has a decreasing front, indicating a decreasing power interval. The Schmidt Trigger is an inverting one. When power decreases, the corresponding gate input is positive. The logic AND operator allows to "Pulse" generator to change the reference current slope, until an increasing power is obtained. "Start" circuit determines the power level when the maximization process begins, after the supply transient process. It is important to note that the power control loop uses no continuous error signal. Here, due to flip-flop circuit, the control has a sequential evolution, based on the power derivative transitions. It is equivalent with a hysteresis control, taking into account the memorized sign of the derivative.

The reference current control may have a recursive representation. For an arbitrary moment t_k, the reference current is a linear variable ramp with S_k slope defined by:

$$S_{k+1} = \begin{cases} S_k \ if \left(D_k - D_{k-1}\right) \geq 0 \\ -S_k \ if \left(D_k - D_{k-1}\right) < 0 \end{cases}$$

where: D_k and D_{k-1} are the power derivative values at t_k and t_{k-1} moments.

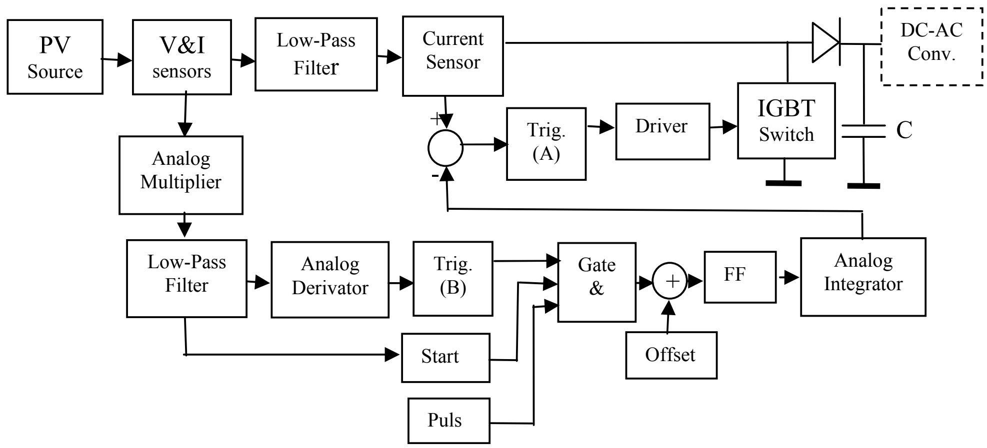

Fig.2. Block functional diagram of DC-DC input converter.

The block diagram has two sections. Power flow circuit contains: Thevenin equivalent source of the PV device, current and voltage sensors, current controlled boost circuit, storage capacitor C. Power control signal circuit contains: analog multiplier, LP filter, analog differentiator, Schmidt-trigger (B), three input logic "and" gate, symmetrization circuit (adder & offset), flip-flop circuit, analog integrator.

For this configuration, several operating characteristics may be pointed out: simplicity and low cost (minimal circuitry and functional blocks); only two states operation modes; characteristics independence of PV device; only power evolution monitoring. Boost circuit is benefic because it can operate at low input voltages, becoming independent from the PV device characteristics. The voltage of output capacitor is controlled only by the input current of an auxiliary output DC-AC converter.

3. Implementation and design considerations

Only simple analog and digital circuits or standard building blocks are used. This hybrid solution, based on analog signal processing and few logic functions, is sufficient for our purposes because the power maximization procedure uses a recursive sequential procedure with no need of fixed exact reference values. Thus, even if an analog differentiator or integrator have low accuracy their action is satisfactory. Moreover, the analog circuits eliminate the resolution problem of finite digital representation of parameters.

The presented solution is characterized by a differential dP/dt type method with only two stable stationary states and continuous variation of reference current. Moreover, reference current slope transition is uniquely determined by power derivative transition. But, this leads to locked states under PV voltage perturbation conditions. In order to maintain procedure convergence, the purposed solution is based on an additional pulse generator. It creates repetitive additional pulse perturbations if power is decreasing. This eliminates the unlocked state, stimulating new (arbitrary) variations of reference current, enabling the initializing and continuation of the maximization procedure. Thus, two effects are obtained. If sharp PV voltage occurs, locked states are eliminated. If no voltage perturbation occurs, additional parasite variations of reference current appear. But, due to the short duration of time interval, these have negligible effect on the stability and convergence of the process.

The electronic schema from Fig. 3 includes: signal processing circuits (analog multiplier, differentiator, integrator and low-pass filters); power circuits (boost circuit and driver, filter capacitor); state circuits (Schmidt triggers and D flip-flop); decision circuit (AND operator); symmetrization circuit (analog adder and voltage reference); “Pulse” and “Start” circuits. The Schmidt trigger hysteresis is determined by low and high trigger levels. “Start” signal maintains the current growth, during the supply transient regime, until the voltage of C1 capacitor reaches a sufficient level for stable operation. “Pulse” signal commands, in a repetitive manner, changes of the reference current slope, as long as the power is decreasing.

Specific for the proposed solution is the continuity of reference current variation, whose slope sign is determined by decreasing transitions of power. Unlike the classical Perturb & Observe strategies, no successive step and test procedures are used, obtaining better resolution and stability.

A correspondence may be stated between functions and circuit components:

- Instantaneous power computing ↔ analog multiplier for voltage & current signals;
- Power signal smoothing ↔ second order low-pass filter;
- Derivative computation ↔ analog differentiator;
- Zero crossing detection ↔ Trigger Schmidt circuit;
- Transition detection ↔ D flip-flop;
- Signal symmetrization ↔ adder and voltage reference;
- Linear ramp generating ↔ analog integrator.

The circuit state transition is controlled by a few digital components. The AND operator output is active high when power derivative, “Pulse” and “Start” signals are high. The D-type flip-flop circuit switches on positive front and acts as state memory. If the power level exceeds the “Start” reference and the power evolution becomes decreasing, the flip-flop switches for every “Pulse”. Two Schmidt-triggers are used. These have bipolar inputs, low triggering level and generate rectangular pulses when the inputs change polarity. Trig(A) and Trig(B) thresholds define the output levels, fixed by reference voltage sources and resistive divisors. Trigger (A) and inductor L determine boost switching frequency, a high value being benefic for current smoothness, but limited by switching possibilities.

The main action of the low-pass (LP) filter is to separate the boost ripple frequency spectrum from the control power ripple frequency spectrum. The boost L-C1 filter acts both on the transferred power variation and on power control signal. Its cut-off frequency is tuned depending on the boost switching frequency, which is relatively high compared with power control loop. The L-C1 filter attenuates the boost ripple, but acts implicitly on measured power signal. Thus, the relative attenuation of power signal harmonics is determined only by second order LP filter (LPF).

Both L-C1 and LPF filters attenuates harmonics in different modes. Capacitor C1 reduces the input boost impedance and filters the voltage signal. Inductance L filters the input current and determines boost switching frequency. For high L values both the switching frequency and cut-off frequency of L-C1 filter are lower. Thus, the separation between this and power loop spectrum by LP filter becomes difficult. For an optimal filtering strategy L and C1 components must filter, respectively, the input current and voltage, in a balanced manner, in order to obtain the lowest spectrum for power signal. Thus, the LPF action may be restricted, with a higher cut-off frequency, obtaining a low phase delay for power loop.

The integrator and the low-pass filter have strong contribution to the signal propagation delay. The differentiator and Schmidt-trigger circuits are responsible for high-frequency switching perturbation. Derivation and integration constants, triggering levels and filter cut-off frequency determine the circuit characteristics.

Following dependencies result between components characteristics and circuit behavior:

- Inductance L & Trigger (A) levels↔ Boost ripple amplitude & frequency;
- Integrator constant ↔ Power variation slope & loop amplification;
- LP filter cut-off frequency ↔ Loop delay & stability margin;
- Trigger (B) ↔ Loop hysteresis (implicitly power ripple frequency and amplitude).

Thus, parameters must be chosen in order to obtain: enough ripple attenuation, reasonable switching frequency, impedance matching, and good dynamics and control stability. Integrator circuit, trigger (B) and LP filter determine the variations of power signal, having strong influence on the overall dynamic and transient regimes.

For good stability, the following tuning procedure is useful: maximize boost switching frequency, balance the current-voltage filtering by L-C1 filter and reduce the cut-off frequency of LP filter for minimal phase delay.

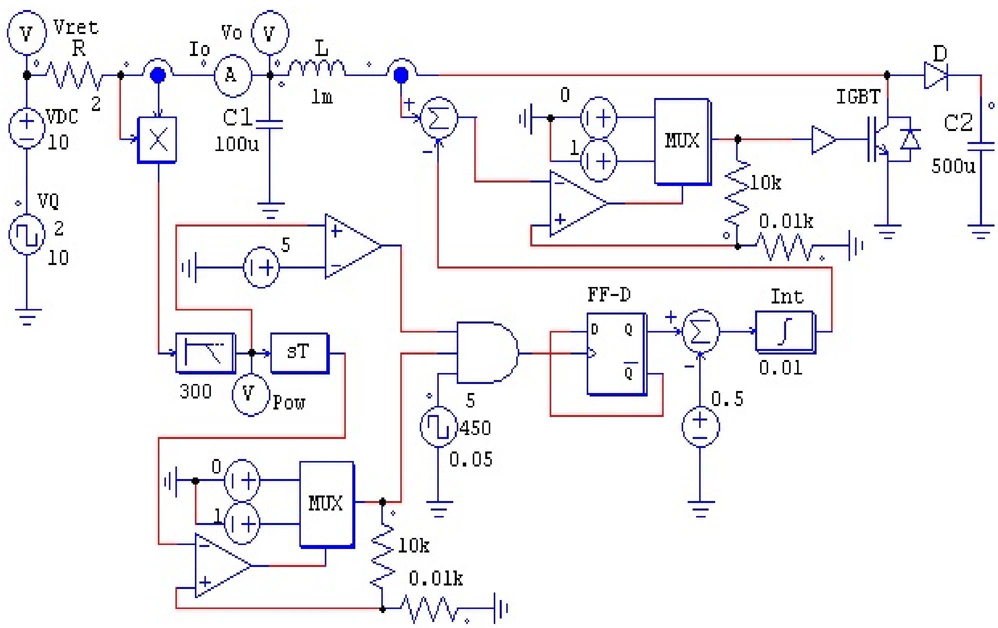

Fig. 3. Circuit diagram of MPPT DC-DC converter.

4. Simulation results

Numerical results obtained with PSIM program are showed in Fig.4. Fast changing operating conditions are modeled by voltage step variation, considering a Thevenin equivalent circuit for PV the device. Its behavior is strongly nonlinear. Its may affect only PV voltage variations, because the current is controlled by the converter. However, for simplicity a constant resistance is considered. This is no loss of generality because the DC-DC converter is impedance adaptive.

In Fig.4 four time dependent parameters are plotted: MPPT converter input voltage and current (Vo, Io), Thevenin equivalent PV device voltage (Vpv) and

the transferred power signal (Pow). With the chosen parameters, the numerical simulations show the following facts:
- Maximal power transfer is obtained (for presumed given impedance);
- MPPT procedure operates for fast changing operating conditions (terminal voltage step);
- Power variation is smooth, voltage and current having opposite variations;
- Stabilization of the transferred power is fast;

The correct MPPT operation may be determined from the resulting power level. After stabilization, at the PV device terminals, the output equivalent impedance becomes equal with the considered Thevenin impedance. Thus, for a conventional considered 2Ω internal resistance and 10V voltage, the resultant value for the transferred power equals 12,5W, corresponds to optimum power transfer, when the DC-DC converter input impedance equals the PV device impedance.

The quality of power control characteristics may be observed on graphical time-dependence evolution, from different points of view:
- Steady state regime of power signal is smooth (unobservable ripple) with a precise numerical value matching the transfer impedance;
- Moderate duration for supply transient regime;
- Good dynamics with low overshoots and high slew-rate on transients caused by PV voltage changing;
- Local and global stable behavior, input power signal having higher smoothing order than the current or voltage;
- Good stability (confirmed by other numerical experiments).

For optimal operation, tuning elements are available:
- Integrator constant for power control dynamics;
- Trigger (B) hysteresis for power control accuracy;
- LP filter cut-off frequency and integrator constant for control loop stability;

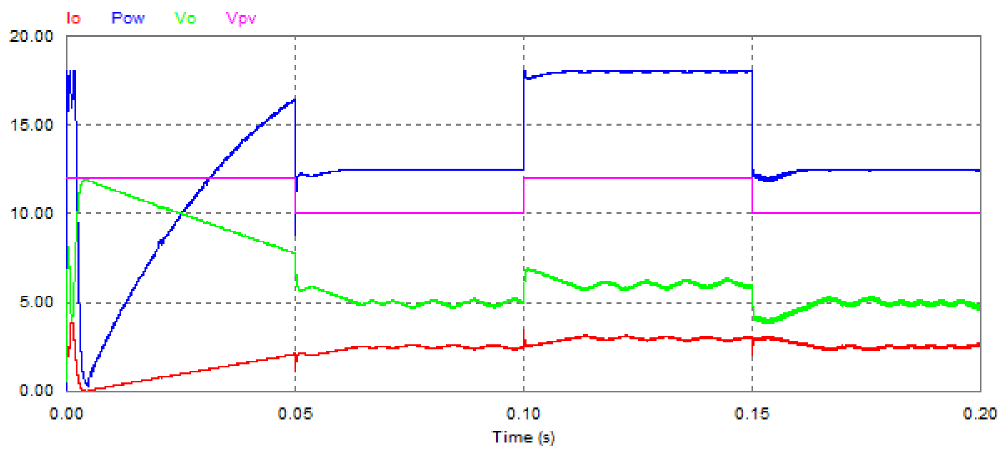

Fig. 4. Time dependence of power, PV equivalent voltage and terminal parameters.

5. Conclusions

The paper target was to find an economical solution for a DC-DC MPPT problem concerning PV devices, using a current controlled boost circuit. The task of voltage stabilization for output capacitor must be achieved by an additional DC-AC converter connected to grid.

This original control strategy is based only on analog circuits, two triggers and a flip-flop circuit. No arithmetic operation and algorithmic sequential control is necessary. This is a low cost solution, enabling simple tuning and understanding. It satisfies load matching with PV device, independent from PV characteristic and environmental conditions dependence.

Despite solution simplicity, the dynamic and precision characteristics are good with no critical limitations. Digital DSP solutions, despite their flexibility and completeness, are expensive, implying a consistent design and programming effort, especially when a good numerical resolution is desired.

The control loop uses no error signal and reference values. The circuit has a dynamic cyclic sequential evolution, based on control parameters with continuous, locally linear, variation. The control acts like a hysteresis feedback loop, but the reference's role is played by the preceding value of the power derivative, the transfer function is transition dependent and asymmetric (acting only on negative front) having a cyclic two states behavior. When non-optimal tuned parameters are used, stability is maintained, but switching phenomena and propagation delay may lead to ripple variation and lower transferred power.

The main feature of the presented solution is the event detection principle. The standard methods use incremental power variations and a-posteriori analysis, resulting supplementary signal delay and perturbations, which may interfere with boost switching frequency.

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