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Fuzzy-predictive direct power control implementation of a grid connected photovoltaic system, associated with an active power filter

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ABSTRACT

The present paper proposes a real time implementation of an optimal operation of a double stage grid connected photovoltaic system, associated with a shunt active power filter. On the photovoltaic side, a fuzzy logic based maximum power point taking control is proposed to track permanently the optimum point through an adequate tuning of a boost converter regardless the solar irradiance variations; whereas, on the grid side, a model predictive direct power control is applied, to ensure both supplying a part of the load demand with the extracted photovoltaic power, and a compensation of undesirable harmonic contents of the grid current, under a unity power factor operation. The implementation of the control strategies is conducted on a small scale photovoltaic system, controlled via a dSPACE 1104 single card. The obtained experimental results show on one hand, that the proposed Fuzzy logic based maximum power taking point technique provides fast and high performances under different irradiance levels while compared with a sliding mode control, and ensures 1.57% more in efficiency. On the other hand, the predictive power control ensures a flexible settlement of active power amounts exchanges with the grid, under a unity power functioning. Furthermore, the grid current presents a sinusoidal shape with a tolerable total harmonic distortion coefficient 4.71%.

1. Introduction

Energy is becoming a key factor in the economic and social development of our society [1]. In recent decades, our planet has experienced an increase in gas emission rates, that was the result of the considerable advancement of technology and the industry [2]. Therefore, the production of electricity by means of suitable (non-polluting) methods has become a prime necessity to meet the power supply of future generations. In this context, the research for alternative energy sources is particularly important because these fossil elements are brought to disappear and cannot renew them before millions of years [3]. Therefore, renewable energies are considered as good alternatives to these dwindling resources. They must be productive enough to replace the current consumption as well as growing demand for energy. They are inexhaustible, clean and can be used in self-directed manner, such as wind, biomass, and solar thermal or photovoltaic [4]. Photovoltaic (PV) energy, considered among the most common energy sources is extensively used around the world, since it can be directly used, with no moving parts [5].

PV panels, called as a finite power source, present a nonlinear P-V characteristic where the extremum, is always tracked through numerous control strategies to permit an adequate use of these sources [6]. Recently, various, more or less complex maximum power point tracking (MPPT) techniques called: extremum seeking methods, have been suggested in literature [7].

Nowadays, several maximum power point tracking (MPPT) methods, based on artificial intelligence, or those called 'global optimization methods provide fast and high performances while compared with the conventional seeking methods: perturb and observe P&O [8], and hill climbing (HC) [9]. The principle of these methods consists on perturbing the system with a constant voltage/duty cycle, and checking its behavior. Under normal irradiance shapes, with no shading effect, such in the present paper, these methods suffer from a noticeable mismatching under sudden irradiance variations, while intelligent MPPT algorithms are proposed to be the best alternatives, in term of accuracy, and rapidity. In [10], a feed-forward back propagation neural network MPPT controller, is used, with three hidden layers, and where the data required to generate the algorithm is inspired from Perturb and observe principle. As noticed, while an optimal choice of hidden

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Nomenclature

MPPT	maximum power point tracking	$\mathbf{R}_{sh}$	PV array series resistance (Ω)
PV	photovoltaic	**V**, **Vr**	actual and reference voltage (V)
DTC	direct torque control	**I**, **Ir**	actual and reference current (A)
DPC	direct power control	**E**, $\mathbf{E_r}$	actual and reference insolation (W/m^2)
P-DPC	predictive direct power control	**ΔT**, **ΔI**	temperature and current variations
THD	total harmonic distortion coefficient	$\mathbf{e_s}_{\ a,\ b,\ c}$	grid voltages (V)
APF	active power filtering	$\mathbf{Is}_{a,b,c}$	grid currents (A)
PI	Proportional-Integral controller	$\mathbf{I}_{\alpha\beta}$	grid currents in αβ reference frame (A)
PLL	phase locked loop	$\mathbf{e}_{\alpha\beta}$	grid voltage in αβ reference frame (V)
FLC	fuzzy logic control	$\mathbf{V}_{a,b,c}$	inverter output voltages (V)
$\mathbf{V}_{PV}$	PV array voltage (V)	$\mathbf{P}_{ref}$	reference active power (W)
$\mathbf{I}_{PV}$	PV array current (A)	$\mathbf{Q}_{ref}$	reference reactive power (Var)
$\mathbf{I}_{sc}$	PV short circuit current (A)	**Ls**	source inductance (H)
$\mathbf{I}_{o}$	diode inverse saturation current (A)	**Rs**	source resistance (Ω)
$\mathbf{V}_{oc}$	PV open circuit voltage (V)	$\mathbf{L}_{L}$	load inductance (H)
Iop	optimal PV current (A)	$\mathbf{R}_{L}$	load resistance (Ω)
Vop	optimal PV voltage (V)	**Lf**	output filter inductance (H)
$\mathbf{V}_{th}$	thermal voltage (V)	**L.P.F**	low pass filter
α	boost duty cycle	**M.V.F**	multivariable filter
β, **γ**	current and voltage change coefficient depending on the temperature	$\mathbf{V_{DC}}$, $\mathbf{V_{DCref}}$	actual and reference DC bus voltage (V)

layers and neurons number is made, a compromise between rapidity and accuracy around the optimum is then obtained. In [11], a fuzzy logic technique is considered as a potential candidate to the ANN technique in normal irradiance shapes, where no off-line training is required. The FLC, inspired from drive control, provides fast response and softness around the optimum through a convenient choice of a symmetrically distributed membership functions. Among different intelligent controllers, the FLC is the simplest to integrate, and its design does not require an accurate mathematical model. In addition, it presents noticeable tracking skills in case of large and sudden irradiance variations. In case of partial shading effect, where the incident irradiance exhibits multiple plateaus, heuristic global optimization methods, such as particle swarm optimization (PSO) [12] and Genetic algorithm (GA) [13], are considered the more suitable, since a global extremum is always obtained through a random search pattern. As described in [12], the well-known 'distributed MPPT architecture' is proposed to improve the energy production with respect to a centralized MPPT technique, and offers additional features in term of protection. It was observed that a trade of between rapidity and accuracy is obtained through a proper choice of iteration and particles number. In [14], the authors analyze the performance of a new Extremum Seeking Control scheme which has two adaptive control loops: the searching loop locates the Global Maximum Power Point by sweeping the Photovoltaic pattern based on an asymptotic dither, while the tracking loop finds and tracks accurately the Global Maximum Power Point based on an asymptotic Perturbed-based Extremum Seeking Control. The robustness of the proposed technique was checked under partially shaded conditions, fast changes of the solar insolation, and environmental noise, while four indicators were chosen to evaluate the algorithm performances. In the same topic, [15] proposes a fast global maximum power point tracking (MPPT) method using current sweeping for photovoltaic arrays under partial shading conditions. The current sweeping test is realized by a DC/DC boost converter with a very fast current control loop, and the obtained experimental shows the ability of the algorithm to handle both uniform and partial shading insolation shapes.

With the rapid growth of nonlinear loads use, in power systems, the quality of the energy supplied to consumers tends to degrade [16]. As a solution, the parallel active power filter (APF) is identified as a flexible solution for harmonic compensation. It is connected in parallel with the grid, and injects continuously currents that correspond at any time to the harmonic components of the currents drawn by the load. In this manner, the current supplied by the source of energy remains sinusoidal. In this context, several research efforts on APF have experienced rapid growth in recent years, and prove that this unit is a suitable solution for reducing harmonic contents in low and medium application [17].

In recent years, researchers are more interested in direct power control (DPC) strategy in various applications, ensuring a decoupled control of active and reactive power and an improvement of dynamic performances. As a sample, this strategy is applied in a direct nine-cells matrix converter [18], in a three-phase PWM rectifier; authors [19], compare the results of the voltage-oriented control (VCO) with direct power control (DPC) applied to a three-level rectifier, On other hand, an application of the DPC control on a two-level rectifier in the presence of unbalanced three-phase system is proposed in [20], and finally on various active power filter topologies [21]. This method, inspired from the famous direct torque control (DTC), applied in electrical machine control, is considered as a suitable alternative to the field oriented control technique [22]. However, this method, which uses a switching table to tune the involved power converter, do not allow to impose explicit criteria or constraints on the quality of controlled instantaneous powers [23]. Furthermore, the direct power control (DPC) has a major drawback associated with the periodicity of the switch control signals, which cannot be controlled. Moreover, it requires a high sampling rate for precise and efficient control of active and reactive power [24]. To remedy these disadvantages, other DPC structures are proposed in literature. These structures are based on an association of the DPC principle with a vector modulation technique (SVM) to obtain a constant switching frequency without using a switching table, or predictive approaches (Predictive Direct Power Control P-DPC), that their use have become wide [25].

The present paper describes how an optimal operation of a small scale double stage grid connected PV system, feeding a non-linear load can be achieved. In fact, choosing a double stage PV system topology revolves around two main points: first, improving