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Model predictive control design for DC-DC converters applied to a photovoltaic system

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ABSTRACT

A continuous control set model predictive control (CCS-MPC) is designed for a DC-DC buck converter used in maximum power point tracking (MPPT) of a photovoltaic (PV) module. A modified incremental conductance (m-INC) algorithm is used for MPP determination as a reference signal for CCS-MPC. The small-signal model of the PV system is adaptively obtained around MPP through linearization of its average model. The predictive control is designed and applied to a PV system using an online optimization of the cost function including the discretized present and future states. The performance of the proposed m-INC CCS-MPC is evaluated by simulation study that indicates better performance in terms of transient and disturbance rejection compared to conventional PI controller. Finally, the applicability of the proposed m-INC CCS-MPC strategy is assessed with outdoor experimental results and the associated practical advantages against finite control set (FCS) MPC are discussed.

1. Introduction

Despite the reduction of solar installation cost by a ratio of 10 during the last 20 years, still conversion efficiency of PV panels remains an important parameter to take into account when designing solar system for residential applications [1]. Therefore, an efficient MPPT algorithm plays a key role to harvest optimum available power especially in large solar installations. Several MPPT algorithms have been elaborated in the literature. Among them, perturb and observe (P&O) and incremental conductance (INC) are practically favorable as the awareness of PV panel characteristics is not required. Moreover, their procedures to find MPP are independent of temperature and irradiation values that their measurements need expensive sensors [2,3]. Principally, P&O and INC are inherently perturbative methods that produce reference voltage or current to be tracked by a subsequent controller. The PI controller has been widely used in MPPT operations [4,5]; however, continuous evolution in microprocessor technology facilitates implementing advanced controllers for efficiency enhancement of MPPT algorithm. The ability of Fuzzy logic [6,7], neural network [8] and genetic algorithm [9] has been investigated in MPPT modules. This paper deals with predictive technique that is lately well adopted for various applications. Indeed, model predictive controller (MPC) is a competitive alternative to address the growing industrial concerns regarding to performance and efficiency issues. It can also formulate inherent nonlinearity in power electronic systems with operational constraints. Moreover, its realization in state matrix can be easily extended to multivariable systems [10]. Basically, MPC solves an optimization problem within a moving time horizon in order to generate future actions for optimal operation of a plant. In fact, at each sampling time, MPC reconstructs instant operating model of the plant, predicts future states and optimizes current dynamic while taking into account the future states. Real time modification is a desirable property in practice that can compensate inevitable modeling errors [11].

In power electronics, MPC were emerged with finite control set (FCS) appearance. Actually the pulse activation nature of switching converters allowed defining FCS-MPC that evaluates cost function in only possible switching states. A low complexity optimization algorithm is solved and simply the minimum cost is selected among predetermined states at each sampling time. FCS-MPC has been investigated in most applications of power converters [12–14], and especially in PV systems [15–18]. Despite numerous reports in this area, the applicability of FCS-MPC is yet a challenge. It works with variable switching frequency which leads to a widespread harmonics spectrum for voltage/current waveforms. This is a fundamental limitation that hinders filter design [19,20], increases switching losses, makes unwanted resonances, and consequently reduces system

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performance in terms of power quality [21]. However, the switching frequency could be regulated by including some more terms in the cost function, it would add the complexity and consequently the computation burden to the FCS-MPCs while distracting control effort from main target of the reference tracking [22,23]. Moreover, none-zero steady state error is reported in [24,25]. Furthermore, the computational burden increases exponentially in multilevel converters with high number of switching states [26].

To address these existing issues of FCS-MPC, this paper formulates continuous control set (CCS) MPC in a PV system supplying DC bus through a buck converter. The CCS-MPC strategy benefits from the average model of the systems and then uses a modulator to ignite the converter switches resulting a fixed switching frequency. The relatively high accuracy of the models for power converters is an opportunity to define complex performance criteria introduced by CCS-MPC to achieve the desired dynamic. Besides, an integrator is augmented in the proposed MPC design in order to comply with steady state requirements. To evaluate the efficiency of the proposed controller, the performances of CCS-MPC is compared to the conventional PI controller while both are using m-INC as MPPT algorithm.

The rest of this paper is organized as follows: the overall configuration of the PV system is demonstrated in section II. The switch model of the PV system is acquired in bilinear compact form. Afterwards, the average model is derived from the switch model to have continuous manipulating variable for the proposed controller. In Section 3, the INC method is modified and elaborated (called m-INC) in order to find real time MPP as the reference signal for CCS-MPC. In Section 4, the methodology of CCS-MPC approach is explained in three stages. The operating point of the system is calculated in first stage. Subsequently, the nonlinear average model of the system is linearized around the operating point that yields small-signal model. Moreover, a discretization is done in this stage for DSP implementation. Secondly, using output and states variations, an augmented system is developed to benefit from an integral control action for steady state purposes. Also, the predicted vectors of states and output in the form of augmented systems are obtained. In the third stage, the optimum duty cycle is generated by real time optimization of a cost function, which is modulated through a PWM block. The performance of the proposed MPC is examined by modeling PV panel and converter in SimPowerSystems of MATLAB software in Section 5. The practical test results of PV set-up are presented and discussed in Section 6 to validate the theoretical and simulation studies.

2. PV system modeling

A practical photovoltaic system is shown in Fig. 1, where power is delivered to an energy storage system through a buck converter. The buck converter is employed in order to control the operating point of PV panel at MPP and it may be replaced with boost or buck-boost

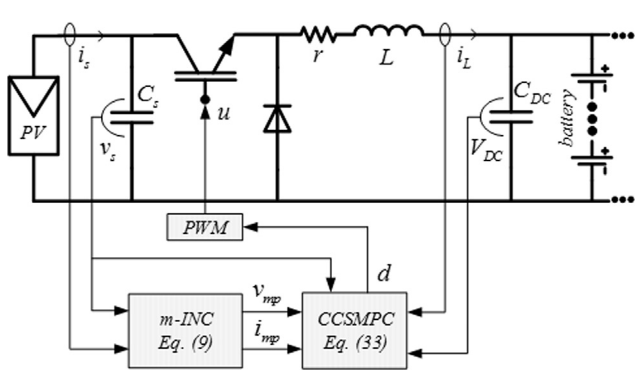

Fig. 1. Schematic of a PV system with block diagram of the proposed control structure.

converters depending on the specific application. In this PV system, the output voltage is kept constant at V_{DC} by a battery or by having a DC to AC converter feeding power to the grid. Moreover, for supplying DC distribution system, an additional controlled converter may be used to stabilize output DC voltage. Furthermore, in grid-connected PV systems, an independently controlled inverter may be used to provide AC voltage. It is worthwhile to mention that in dark condition, the voltage of PV panel may be less than V_{DC}, so if there is no blocking diode, the battery would flow a current with opposite direction that discharges the battery. As blocking diodes are usually included in the construction of PV panels, no more diodes are considered in Fig. 1. Moreover, the battery voltage V_{DC} is known and measured only for rejecting disturbances on DC bus voltage.

The converter is driven by switching signal $u(t)$ generated through PWM. The signal $u(t)$ is defined in Eq. (1) with period T and duty ratio d.

$$u(t) = \begin{cases} 1 & 0 \leqslant t < dT \\ 0 & dT \leqslant t \leqslant T \end{cases} u(t-T) = u(t)\ \forall\ t \tag{1}$$

Applying the Kirchhoff's laws on the circuit of Fig. 1 distinctly in two switching states 0 and 1, a single unified model in a compact form can be presented by Eq. (2). This model is called switched model as it describes switching dynamics of power electronic converters.

$$\begin{cases} -i_s(t) + C_s\frac{dv_s(t)}{dt} + u(t)i_L(t) = 0 \\ -u(t)v_s(t) + ri_L + L\frac{di_L(t)}{dt} + V_{dc} = 0 \end{cases} \tag{2}$$

In control theory, it is desired to work with a continuous manipulating signal than two switching states of $u(t)$ [27]. Using definitions in Eqs. (3)–(5), averaging technique is employed to transform the discontinuous model of Eq. (2) to the continuous model of Eq. (6) for CCS-MPC algorithm. The symbol x_0 signifies average operation on x; however, the previous symbols are used again in Eq. (6) for simplicity, but duty ratio $d(t)$ is substituted as the average variable of $u(t)$ in sliding period of T.

$$\langle x(t)_0\rangle(\mathrm{t}) = \frac{1}{T}\int_{t-T}^{t} x(\tau)d\tau \tag{3}$$

$$\left\langle \frac{dx(t)}{dt} \right\rangle_0 (t) = \frac{d}{dt}\langle x(t)\rangle_0 \tag{4}$$

$$\langle x(t)u(t)\rangle_0(t) \approx \langle x(t)\rangle_0(\mathrm{t})\langle u(t)\rangle_0(\mathrm{t}) \tag{5}$$

$$\begin{cases} \frac{dv_s(t)}{dt} = \frac{1}{C_s}(i_s(t) - d(t)i_L(t)) \\ \frac{di_L(t)}{dt} = \frac{1}{L}(-ri_L(t) + d(t)v_s(t) - V_{dc}) \end{cases} \tag{6}$$

The system of Eq. (6) is not an exact model of the PV system, however, adequately represents low frequency behavior of signals while neglecting high frequency components caused by switching action. It is a natural practice since high-frequency switching phenomena are parasitic contents in most power electronics applications that are eliminated by filters [28].

2.1. MPPT algorithm

In this section, INC with some modifications is used to determine the reference signals for MPC [2]. Simply, the output power of PV panel is described as:

$$p_s(t) = v_s(t)i_s(t) \tag{7}$$

The slope of power signal with respect to the output voltage of the panel can be stated as Eq. (8), where g and dg are conductance and differential conductance, respectively.