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IMAD ELZEIN, YURY N. PETRENKO

MODEL PREDICTIVE CONTROL FOR PHOTOVOLTAIC STATION MAXIMUM POWER POINT TRACKING SYSTEM

Belarusian National Technical University

The purpose of this paper is to present an alternative maximum power point tracking, MPPT, algorithm for a photovoltaic module, PVM, to produce the maximum power, Pmax, using the optimal duty ratio, D, for different types of converters and load matching.

We present a state-based approach to the design of the maximum power point tracker for a stand-alone photovoltaic power generation system. The system under consideration consists of a solar array with nonlinear time-varying characteristics, a step-up converter with appropriate filter.

The proposed algorithm has the advantages of maximizing the efficiency of the power utilization, can be integrated to other MPPT algorithms without affecting the PVM performance, is excellent for Real-Time applications and is a robust analytical method, different from the traditional MPPT algorithms which are more based on trial and error, or comparisons between present and past states. The procedure to calculate the optimal duty ratio for a buck, boost and buck-boost converters, to transfer the maximum power from a PVM to a load, is presented in the paper. Additionally, the existence and uniqueness of optimal internal impedance, to transfer the maximum power from a photovoltaic module using load matching, is proved.

1. Introduction

Solar energy is one of the most important alternatives energies with applications in urban areas, motor drives and with no alternative for spacecraft and space station application. [1]–[8] etc. It is expected that solar energy is growing from $91,6 billion in 2011 to $130,5 billion by 2022.

A photovoltaic PhV module, (PhVM) as the number of PhV sells, is the key component to convert solar energy into electric energy [1], [4], [8]. In addition to the PhVM, a typical photovoltaic system PhVS configuration consists of storage capacitance, DC-DC converter, and batteries [1]. In most of the applications, it is always desired to obtain the maximum power from a PhVM, due the fact that the PhVM operates at the highest efficiency [3]–[4]. The maximum power point tracker, MPPT, is the typical algorithm to calculate the maximum power, Pmax, provided by a PVM [3], [4], [6].

The task of a maximum power point tracker (MPPT) in a photovoltaic (PV) energy conversion station PhVS is to continuously tune the system so that it delivers maximum power from the solar array regardless of weather or load conditions. The solar array model has a nonlinear voltage-current and voltage-power characteristic, as it is shown in Fig. 1 [1] and more than that the working conditions mainly as insulation, ambient temperature, and wind that affect the output of the solar array are unpredictable, the MPPT must designed to contend with a nonlinear and time-varying system. Many tracking algorithms and techniques have been developed by different authors in recent years – on-line and off-line ones [4], [7], [9].

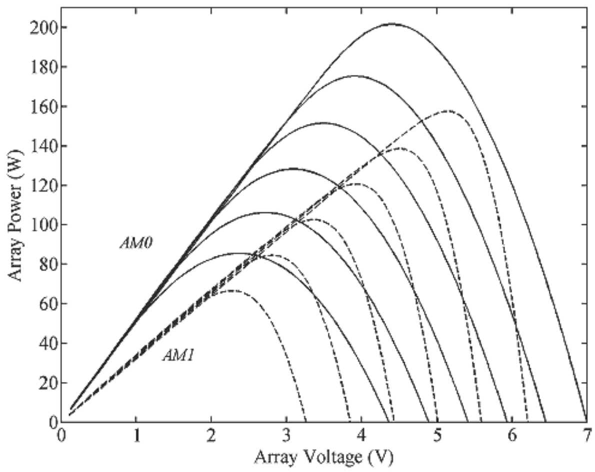

Fig. 1. Array power versus its voltage for the temperature of (from right to left) 273,300, 325,350,375, and 400 K. Solid lines for AMO (air mass) condition, and dash lines for AM1 condition

Unfortunately, most of the existing MPPT methods to estimate the maximum power are based on trial and error algorithms where the voltage is increased until the maximum power is achieved, better known as the hill-climbing method [5]–[7]. Other MPPT algorithms compare the last sampled voltage and current versus the presently sampled voltage and current to see which state will produce the maximum power.

Additionally, the literature offers other types of MPPT algorithms such that. The Perturb and Observe (P&O) method and the Incremental Conductance (InCon) method, as well as variants of those techniques are the most widely used. The (P&O) method is known for its simple implementation, but during normal conditions it deviates from and oscillates around the maximum power point, since the system must be continuously perturbed in order to detect the maximum power point. Furthermore, the P&O method oscillates close to the maximum power point (MPP), when atmospheric conditions are constant or slowly changed. However, when weather rapidly changes, the P&O method fails to track the maximum power point effectively.

There are some other methods for solar array MPP tracking, based on parameters of solar panel, include short circuit current [2] and the open circuit voltage of the PV module techniques [6], [7]. The MPP tracking method using the short circuit current of the PV module exploits the fact that the operating current at the MPP of the solar array is linearly proportional to its short circuit current. Thus, under rapidly changing atmospheric conditions, this method has a relatively fast response time for tracking the MPP. However, the control circuit is still somewhat complicated and both the conduction loss and the cost of the MPPT converter are still relatively high [3]. Furthermore, the assumption that the operating current at the MPP of the PV module is linearly proportional to the short circuit current of the PV module is only an approximation. In reality, the application of this technique always results in PV module operation below the maximum power point.

In this paper, we present a state-based approach to the design of the maximum power point tracker for a stand-alone photovoltaic power generation system. The system under consideration consists of a solar array with nonlinear time-varying characteristics, a DC-DC converter with appropriate filters, and a load subject to disturbances. A state space model for the system is established using a time-averaged switch model. A nonlinear time-varying dynamic feedback controller is developed based on the structural information of the original system and the conditions for maximum power delivery.

2. Model Predictive Control Basement

As the complexity of processes and increasing requirements for their occurrence, environmental, energy, and improve the safety of care, and complicated management system, which, as a rule, are based on computer technology and digital control systems.

Despite the fact that in a real industrial automation still prevalent digital control system based on the PID control [5], all the more common systems and algorithms based on adaptive and optimal control, including with artificial intellect-based: Fuzzy logic, Neuron systems [8], [10], [11] which is very important for non-linear systems and high-order systems.

One of the modern approaches to formal analysis and synthesis of control systems based on mathematical optimization techniques, is the theory of control of dynamic objects using predictive models – *Model Predictive Control (MPC) – adaptive predictive control is a model that has received considerable development in the last decade. Its basic idea is to use a certain depth extrapolated values of the variables in the formation of the control law so as to minimize future system deviation from the desired state and thereby ensure optimal control.*

Basics MPC, i. e. is a model-based on line control approach with the following parts: a prediction horizon, a receding horizon procedure, and a regular update of the model and re-computation of the optimal control input [12], [13], [14], [15], [16].

This approach began to develop in the early 60s for the management of processes and equipment in the petrochemical and energy production, for which the use of traditional methods of synthesis have been extremely difficult due to the exceptional complexity of mathematical models. The earliest algorithm of Model Predictive Control (MPC), proposed by French engineer Richalet and his colleagues in 1978, was based on the

Model Predictive Heuristic Control (MPHC). Since then the explicit background of industrial application has made MPC develop rapidly to satisfy the increasing demand from modern industry. The unique feature of MPC which differs it from many other control algorithms, lies in the research history of MPC which originated from application and then expanded to theoretical field, while many other control algorithms, as an idea, often has applications after sufficient global theoretical research [17]. Currently, the scope of application of practical methods of MPC-expanded considerably, encompassing a variety of processes in the chemical and construction industries, light and food industries, aerospace research, modern systems of energy and so on. Number of publications and researches is increasing annually.

Authors in [17] proposed certain extensions and adaptations of the MPC for some tractable classes of discrete-event systems which leads to some extensions and adoptions of the MPC framework to classes of hybrid systems.

There are several *popular definitions of hybrid systems, which are popular in such areas of industry as traffic control, robotics, aircraft, and plant process control including Maximum Power Point (MPP) control of Photovoltaic (PhV) Stations.*

Some authors [18], [19] define a hybrid system as a coupling of a continuous-time or analog system and a digital system or discrete-time system.

In real application it usually leads to a combination of continuous-time (analog) plant and a digital controller, which acts in asynchronous manner. Actually hybrid systems arise from the combination between continuous-variable systems and discrete-event systems. Hybrid system can be in one of several modes of operation; each mode of behavior of the system can be described by a system of difference or differential equations and the system can be switched from one mode to another because the to the occurrence of events. The transition can be caused by an external control signal or by combination of state variables itself, i. e., when a state boundary reached desired level.

Hybrid systems can be analyzed by many modeling techniques. The most popular of them are [19] predicate calculus, real-time temporal logics, timed communicating sequential processes, hybrid automata, Petri nets, and object-oriented modeling languages such as Modelica, SHIFT or Chi. It should be noted that special mathematical analysis techniques have been developed for some subclasses of hybrid systems.

The main advantage of MPC-approach, determining its successful use in the practice of construction and operation of control systems [12], [14], [15], [16], [17] is the relative simplicity of the basic scheme of formation of feedback, combined with high adaptive properties. The latter allows to manage multidimensional and multiply objects with complex structure, consisting of non-linearity, optimize processes in real-time within the constraints on control and manipulate variables to take into account the uncertainty in the job sites and disturbances. In addition, the possible delay taking into account transport, accounting for changes in quality criteria in the process and sensor measurement system failure.

Being MPC-approach is the following scheme of control of dynamic objects of feedback:

1. We consider some (relatively simple) mathematical model of the object, the initial conditions for which serves as its current status. For a given program management performed integration of the equations of the model that predicts the motion of the object at a finite time interval (the forecast horizon).

2. Running optimization software management, the purpose of which is the approach of controlled variables predictive model to the respective drive signals on the horizon of the forecast. Optimization is carried out taking into account the whole complex of constraints imposed on the control and controlled variables.

3. In step calculations, constituting a small part of a fixed forecast horizon, realized the found optimum control and the measurement is made (or restoration of the measured variable) the actual state of the object at the end of step.

4. Forecast horizon is shifted to step forward and repeat steps 1–3 of the action sequences.

This scheme can be combined with carrying out preliminary identification of the model equations used to perform prediction.

The idea of optimizing the projected software movement is the basis of MPC-practices arose within two separate but substantially similar approaches. The first of these, called Dynamics Matrix Control (DMC), developed efforts of specialists of the company Shell Oil in the mid-60s [17], and the second – Model Algorithmic Control (MAC) – was developed by French engineers of chemical industry in the late ‘60s [19]. On the basis of the latter approach was first established commercial software package IDCOM (Identification and Command), which to some extent served as a prototype of modern software support management prediction.

Currently, MPC-approach is under intensive development, as evidenced by the extensive bibliography published in recent years, scientific papers on this subject. Development of ideas feedforward control occurs in the direction of using non-linear models, ensuring Lyapunov stability of controlled movements, giving the robust features of a closed system of governance, the application of modern optimization techniques in real-time, and others.

The basic foundations of theoretical propositions on which to base all the tools package MPC Tools. The presentation begins with a non-linear problem in continuous time [17], which is for the introduction of the topics under discussion.

Further, significant attention is paid to the basic problem of the package – the control of linear discrete plant, the model of which is shown in the state space, using the predictive model is excluding and taking into account the constraints on the control and the state.

3. Generalized nonlinear predictive control. [12], [15]

Assume that the mathematical model of the control system can be presented [12], [13] by a system of ordinary nonlinear differential equations

$$\dot{\boldsymbol{X}}(t)=f\left(t,x(t),u(t)\right),\boldsymbol{X}(0)=x_{0,} \quad (1)$$

where $\boldsymbol{X}\in\boldsymbol{E}^{n}$ – the state vector; $\boldsymbol{u}\in\boldsymbol{E}^{m}$ – the vector control, $\boldsymbol{t}\in[0,\infty)$.

Let us consider the set of admissible control and status, believing that for any fixed point in time must comply with the conditions. Suppose that for any piecewise continuous functions with values of the plurality of function satisfies the conditions of existence and uniqueness of solutions of the Cauchy problem for the system (1). In addition, we assume the system (1) has zero equilibrium position.

In the simplest embodiment allowable assignment sets **U** and **X** can lead, for example, the ratio of:

$$\boldsymbol{U}=\{\boldsymbol{u}\in\boldsymbol{E}^{m}:u_{i\,\min}\le u_i\le u_{i\max},\ i=\overline{1,m}\},(2)$$

$$\boldsymbol{X}=\{\boldsymbol{x}\in\boldsymbol{E}^{n}:x_{j\,\min}\le x_j\le x_{j\max},\ j=\overline{1,n}\},\ (3)$$

where, $u_{i\,\min}$, $u_{i\max}$, $x_{j\,\min}$, $x_{j\max}$ given real numbers.

We assume that the purpose of the control object (1) is to ensure that the equalities

$$\lim_{t\to\infty}\boldsymbol{x}(\boldsymbol{t})-\boldsymbol{r}_x(\boldsymbol{t})=0;\quad \lim_{t\to\infty}\boldsymbol{u}(\boldsymbol{t})-\boldsymbol{r}_u(\boldsymbol{t})=0,\ (4)$$

where a given vector function $\boldsymbol{r}_x(\boldsymbol{t})$ and $\boldsymbol{r}_u(\boldsymbol{t})$ define a desired motion of the object.

We introduce the concept of quality control, setting a functional

$$\boldsymbol{J}_{0=}\boldsymbol{J}_0(x(t),u(t)) \quad (5)$$

to control the movement of the object (1).

Any optimal control problem is to find such a control action of a given class (if the task takes into account the feasible set **U**), which ensures the achievement of goals (4) taking into account the constraints $x(t)\in X$ and $\forall t\in[0,\infty)$ and minimizes the functional (5).

At present there are numerous options for common tasks, concretizing the above general formulation, as well as a variety of approaches to their analytical and numerical solutions. However, it should be noted that to date, all of these approaches are quite complex for practical implementation.

One of the major reasons hampering the use of classical optimization approaches in creating control systems for complex objects, is that the mathematical model (1), which exhaustively presents the dynamics of the real object, because of the many different circumstances we do not know and, in principle, can not be constructed.

To account for this fact in solving problems of optimal control are currently used various ways, one of which is the application of the theory of model predictive control. Essentially, it is the basis of a generalization of the well-known principle of feedback, according to which the formation of the control action use the measured information on the state of the object.

To explain the basic tenets of the theory of predictive control, along with a mathematical model (1) of the control object, we consider a system of differential equations of the form

$$\dot{\bar{\boldsymbol{X}}}_i(\boldsymbol{\tau})=\bar{\boldsymbol{f}}\left(\boldsymbol{\tau},\bar{\boldsymbol{x}}(\boldsymbol{\tau}),\bar{\boldsymbol{u}}(\boldsymbol{\tau})\right)\bar{\boldsymbol{x}}\Big|_{\boldsymbol{\tau}=\boldsymbol{t}}=\boldsymbol{x}(\boldsymbol{t}),(6)$$

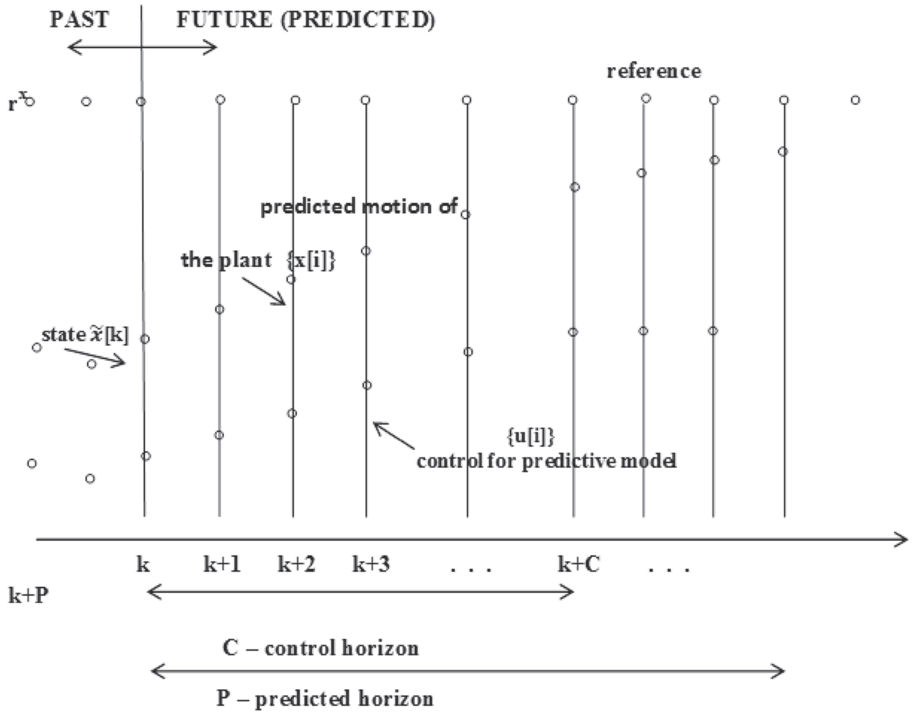

Fig. 2. Predictive plant movement

where $\bar{X} \in E^n$ – the state vector, $\bar{u} \in E^m$ – the vector control, $\tau \in [t, \infty)$.

We assume that the function $\bar{f}$ has the same properties as the function f and vectors $\bar{X}$ and $\bar{u}$ taking the value of the admissible sets, X and u respectively.

In addition, let us assume that the function $\bar{f}$ is set in such a way that for any admissible control $\bar{u}(\tau) \equiv u(\tau)$ vector functions $x(\tau)$ and $\bar{x}(\tau)$, satisfy the system (1) and (6), respectively, are close to each other at a rate for each $\tau \in [t, \infty)$.

The system of differential equations (6) is called predictive model in relation to the mathematical model (1) of the control object.

Prediction circuit implementation on the best is illustrated form presented by [12], Fig. 2.

Here on the x-axis Cartesian postponed times τ, and for the initial moment, it is assumed that $\tau = T$. Up to this point the control object with an unknown exact model of the form (1) moving under the influence of $u(\tau)$ a given control implemented feedback system, and at the time was in a state.

Let's set some control as a function of time interval and integrate the system (6) at a specified interval with the initial condition. The resulting partial solution will be interpreted as the predicted behavior (prediction of the behavior) of the control object from the prediction horizon.

Immediately, we note that, due to the natural differences between the dynamics of a real object and a predictive model of traffic on the segment will be considered as a whole different, but the coincidence is guaranteed only at the starting point.

Now we can formulate a mathematical problem of choosing the optimal control based on the forecast. We assume that the purpose of management is to provide a predetermined pattern of behavior (6), it is determined as in (4), and vector functions $r_x(t)$ and $r_u(t)$, where $X \in E^n$ – the state vector; $u \in E^m$ – the vector control, $t \in [0, \infty)$.

By introducing a MPC approach a constrained optimal control algorithm is formulated and applied in a receding horizon fashion [12].

Through the explicit MPC paradigm, a model is derived based on the physical characteristics of the plant and a control problem is formulated by directly taking into account system constraints and objectives.

In this case the resulting minimization problem can be resolved offline, supersizing the necessity for any on line optimization.

A practical view of photovoltaic energy conversion station is presented on Fig.3, where the source of energy, represented by the solar array PHVS with filter C1 delivers power to DC-DC

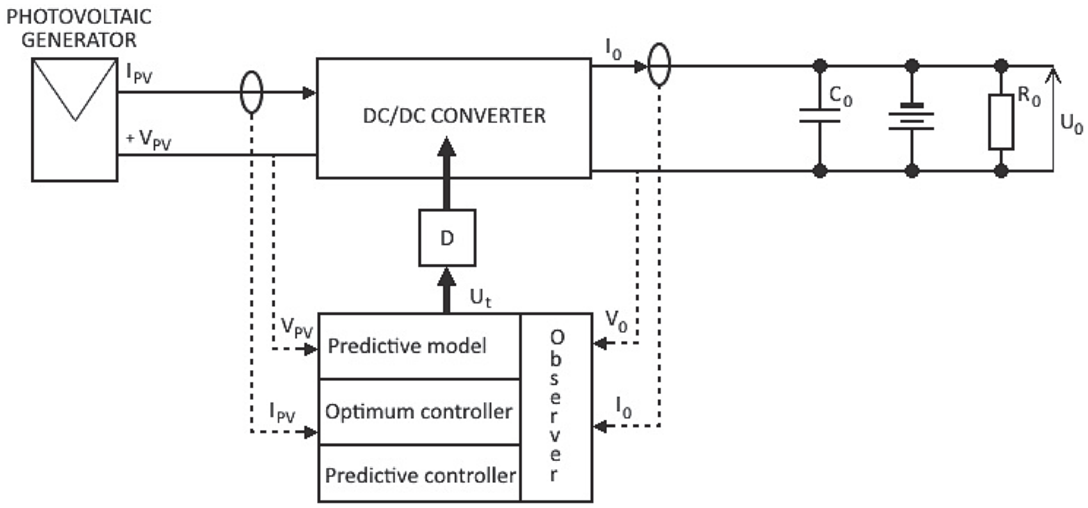

Fig. 3. Photovoltaic station model predictive control block diagram

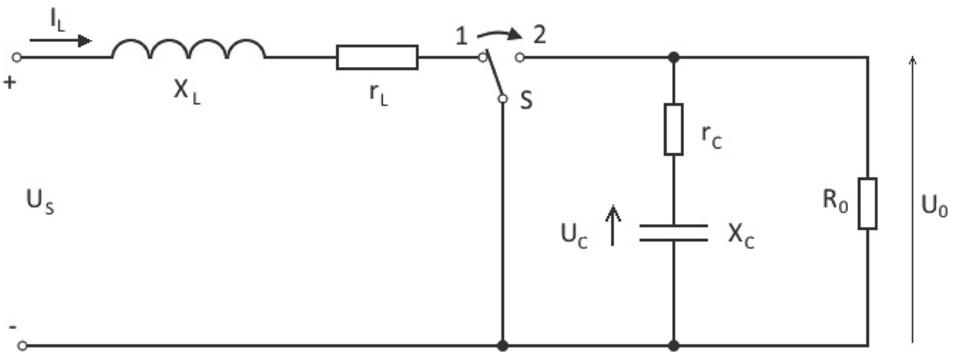

Fig. 4. Lumped parameter model of the boost converter

power converter, the type of which (the most popular are buck, boost or buck-boost converters) depends on specific architecture of the entire system. For instance, if PHVS is to supply power to a DC distribution network (i. g. a space station power network) than power interface is to provide conditioned DC power. In case of smart-home application with AC power distribution network then independently controlled DC-AC inverter with built in Pulse Withdraw Modulation control may be used.. The interface links between PHVS and the consumer grid may include other elements such as energy-storage devices (i. e. batteries or super capacitors), which require specific controllers to run «charge-discharge» mode of operation. In this paper we do not discuss specific control strategies and design of interfacing devices.

The objective of DC-DC converter on PHV station MPPT system is regulate the output voltage V_0 (Fig. 3) under wide range of operations and PHV nonlinearity characteristics, caused by income atmosphere conditions, Fig. 1 and load variation. The controller is to deliver output signal D (Fig. 3) to follow MPPT [7] and constraints of the circuit [2].

DC-DC boost converter schematics in a view of lamped parameter circuits used for control design presented in Fig. 4. For the sake of generality DC-DC buck converter schematics presented in Fig. 5.

A few assumptions (constraints) are needed to explain.

The coil non-linearity's neglected. and the switch is also considered as ideal. At each switching instant, the stray inductor and parasitic capacitor are also neglected. After this assumptions the lamped parameter switched model X_l represent the linear inductance value associated to the coil L, which losses are accounted for r_l; x_c and r_c represent capacitance and equivalent series resistor of C.

Output load presented by resistor r_0. The switching stages of the converter are formalized through the switch S, representing the dually operated semiconductor component. The converter

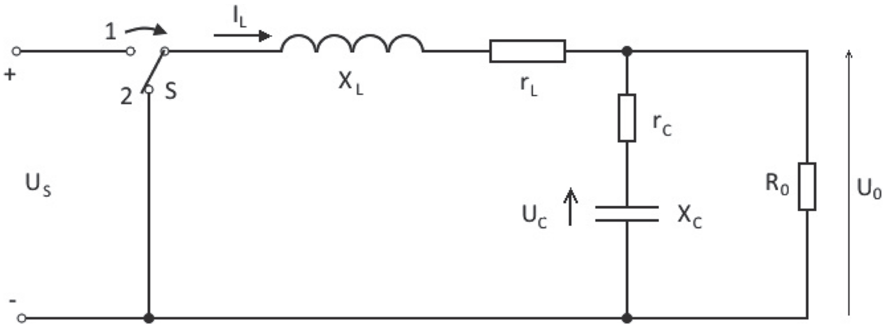

Fig. 5. Lumped parameter model of the buck converter

operation characterizes by switching period T_s (corresponding frequency f_s).

The DC component of the output voltage regulated through the duty cycle $D[k]$, (Fig. 3), which is defined by

$$D[k] = \frac{t_1[k]}{T_s} \tag{7}$$

where $t_1[k]$ represent the time interval during the k-th switching period T_s during which S is in the position 1 for the boost converter, connecting to the supply U_s.

Let us define

$$x(t) = [i_l(t)u_c(t)]^T \tag{8}$$

as the state vector, where $i_l(t)$ is the inductor current and $u_c(t)$ is the capacitor voltage, and with a given duty cycle $D[k]$ for the k-th period, the systems can be describeв by the following continuous-time state-space equations

$$\dot{x}(t) = G_1x(t) + g_1u_s \quad kT_s \le t < (k + D[k])$$

when $VT = 1$

$$\dot{x}(t) = G_2x(t) + g_2u_s \quad (k + D[k])T_s \le t < (k+1)T_s \tag{9}$$

when $VT = 0$,

where $G_{1,} G_2, g_1, g_2$ are given by

$$G_1 = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \tag{10}$$

for the boost converter and

$$G_2 = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}, \tag{11}$$

for the buck converter.

In equations (10) and (11) it is noted

$$a_{11} = r_l/L; \;\; a_{22} = -1/C(r_o + r_2); \;\; a_{21} = a_{12} = 0;$$

$$b_{11} = -(1/L)((r_1 + (r_or_c)/(r_o + r_c)); \; b_{12} = 1/L(r_o/(r_o + r_c); \tag{12}$$

$$b_{21} = (1/C)\,(r_o/(r_o+r_c); \;\; b_{22} = (-1/C)\,(1/(r_o+r_c);$$

$$g_1 = g_2 = \begin{bmatrix} 1/L \\ 0 \end{bmatrix}. \tag{13}$$

Output of the converter u_o is equal to

$$u_o(t) = B_1^T x(t), \;\; kT_s \le t < (k + D[k])T_s,$$

$$u_o(t) = B_2^T x(t), \;\; (k + D[k])T_s \le t < (k + 1)T_s \tag{14}$$

$$B_1 \begin{bmatrix} 0 \dfrac{r_0 r_2}{r_0 + r_c} \end{bmatrix}^T \tag{15}$$

$$B_2 \begin{bmatrix} \dfrac{r_0 r_2}{r_0 + r_2} \dfrac{r_0}{r_0 + r_c} \end{bmatrix}^T \tag{16}$$

Once the reference trajectory is defined as $X_r[k + 1]$ we should follow classical tracking problem. In following we consider a prediction structure as the control strategy for the boost converter.

The control aims to minimizing a quadric function of the prediction error between the reference trajectory $X_r[k + 1]$ and a predicted state $X_p[k + 1]$.

The function which should be minimize is in the form

$$L = (X_p[k + 1] - X_r[k + 1])^2 Q_p + m_p(dd_p)^2 \tag{17}$$

and the minimization is performed with respect to the duty cycle variation

$$dd_p = d_p[k] - d_p[k-1]. \tag{18}$$

In (17) L and m_p is a positive constant and Q_p is a positive definite matrix.

The predictive state X_p is obtained at $(k+1)$ from $X_p[k]$ as

$$x_p[k + 1] = E_1(x_p[k], d_p[k]) + E_2(x_p[k], x[k]), \tag{19}$$

where $x[k]$ is the system real parameters measurement;

E_1 represents the future states without correction

$$E_1(.) = \exp(FT_s)x_p[k] + \\ + F^{-1}\exp(FT_s)(1 - (\exp(-FT_s d_p[k])) \quad (20)$$

The minimization of L can be calculated analytically by $dL/d(d_p) = 0$ or numerically by using the Newton algorithm with only one iteration as suggested in [19]. So, the aim of this control is to calculate $x[k]$ and $x_p[k]$ for the next period of modulation.

Total predictive control scheme consists of the following steps:

Measurement and evaluation of the state vector of the real object. 2. The solution of the optimization problem for the predictive model (6) with the initial condition with respect to the quality functional. 3. Using the best features found in the software as a control segment. 4. Changing the date and time at the time of repeating the steps referred to p. 1.

This sequence of operations is implemented in a control system with feedback; a block diagram is shown in Fig. 3.

It should be noted another important factor. Even if the information about the object enters the regulator continuously, in general, there must be some finite time to solve the optimization problem, which are usually carried out by approximate numerical methods. Consequently, the control corresponding to the resulting state will be applied to the object with the inevitable delay.

Summing up the consideration of the generalized non-linear problem, as the findings point to the following features shown predictive control scheme.

Conclusion

As a predictive model can be used non-linear system of ordinary differential equations. The approach allows to consider the limitations that are imposed on the control variables, and the components of the state vector. The approach involves the minimization of the functional of the quality control process, in real time. To manage the predictive imperative that the current state of the object is directly measured or estimated. The predicted behavior of the dynamic object will generally differ from the actual movement. To work in real time is necessary to the solution of the optimization problem was carried out quickly enough within the allowable delay. The immediate implementation of the schemes considered MPC-strategy does not guarantee the Lyapunov stability of the object which requires special measures to ensure it.

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Imad ELzein, Ю. Н. Петренко

ПРОГНОЗИРУЮЩАЯ МОДЕЛЬ УПРАВЛЕНИЯ СИСТЕМОЙ ОБЕСПЕЧЕНИЯ МАКСИМАЛЬНОЙ ВЫХОДНОЙ МОЩНОСТИ ФОТОЭЛЕКТРИЧЕСКОЙ СТАНЦИИ

Представлен альтернативный подход по обеспечению режима максимальной выходной мощности (МВМ) фотоэлектрической станции (ФЭС).

Рассматриваемая система состоит из солнечных батарей с нелинейными нестационарными характеристиками, работающих в автономном режиме, импульсного преобразователя постоянного тока (ИППТ) повышающего типа и соответствующего фильтра на выходе.

Для управления ИППТ предлагается использовать прогнозирующую модель, теория которой активно разрабатывается в последнее время отечественными и зарубежными учеными.

Приводятся уравнения в пространстве состояний и функциональная схема ФЭС. Особенностью системы является возможность работы в реальном времени и наличие наблюдателя нагрузки.