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SIMULATION STUDY ON ONE-STEP AHEAD CONTROL OF A PHOTOVOLTAIC ENERGY STORAGE SYSTEM

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Abstract: Solar cell which transforms the light energy into the electric energy from Sun comes into prominence as a new energy for next generation. However, it is difficult to obtain the stable output voltage and current from the solar cell due to the uncertainty in weather conditions, etc.

In the present paper, two types of control laws are considered for regulating the input voltage in a photovoltaic energy storage system such as the system with the super conducting magnetic energy storage.

(1) One is the design of optimal controller.

(2) The other is that of weighted minimum prediction error controllers(weighted one-step ahead controllers).

Simulation study for the above controllers is performed to see how they work and to get preliminary knowledge in the regulation of the input voltage to the experimental photovoltaic energy storage system.

1. Introduction

Recently, much attention has been forcused on exploiting and utilizing energy sources such as solar energy for generation of electric power since not only escalation of the cost of energy derived from various conventional and non-renewable energy sources but also the destruction of natural enviroment.

It has been proven that the photovoltaics is extremely reliable and efficient for a wide range of applications. Substantial research and development work in photovoltaics has been done and is being continued by many scientists to reduce the cost of solar cell[1]-[2]. It is pointed out[1] that the importance of controls for the proper design and efficient operartion can not be overestimated and the same research effort as in the meterials and devices research is not paid in this area.

This paper is to address control aspects of photovoltaic systems which is connected to super conducting magnetic energy storage(SMES)[3]-[4] to store the electric energy. We pay attention mainly to the theoretical and numerical aspects of control laws that may be applied for the photovoltaic energy storage system, in order to get the preliminary knowledge necessary for implementing them in the real experimental photovoltaic energy storage system. Two types of control laws are presented. One is the well known optimal control law[5]-[6] and the other is the weighted minimum prediction error control laws(weighted one-step ahead control laws) which are the extentions of those developed for the discrete-time systems[7].

Problem statement is given in Section 2. Sections 3 and 4 present the designs of optimal controller and minimum prediction error controllers, respectively. In Section 4-1 the usual weighted minimum prediction error controller is designed for the continous-time system and in Section 4-2 the stabilized version follows. The results of numerical simulation study are shown in Section 5 and conclusion follows in Section 6.

2. Problem Statement

It is well known that the equivalent circuit of solar battery is represented by Fig.1 and that the output voltage v(t) and current i(t) of a solar cell(one unit) obeys the V-I characteristic equation given by

$$i(t)=i_p(t)-i_0[\exp\{c(v(t)+i(t)R_s)\}-1] \quad (2\text{-}1)$$

where

$i_p(t)=5p(t)(\mathrm{mA})$=short circuit current,

$p(t)=P_{max}\sin[\pi(t-t_1)/(t_2-t_1)](\mathrm{mW/cm^2})$ =insolation or solar radiation(P_{max} is maximum value of insolation),

$i_0=2.92T^3\exp(-eE_g/aKT)(\mathrm{mA})$ =saturation or dark current,

$c=e/AKT$, $A=5a=8.33$, $E_g=1.13(\mathrm{eV})$, $R_s=0.3\times 10^{-3}(\mathrm{k\Omega})$,

and t_1 is sunrise time, t_2 is sunset time, $e=1.6020\times 10^{-19}$(coulombs) is electric charge, A is coefficient determined by the material of the solar cell, $K=1.38\times 10^{-23}$(J) is Boltzmann's constant, T is absolute temperature of solar cell.

Equation (2-1) represents the model of photovoltatic cell. If n solar cells in series are connected to m solar cells in paralell, the total output voltage and current characteristics(or V-I chracteristics) results in

$$i(t)/n=i_p(t)-i_0[\exp\{c(v(t)/m+i(t)R_s/m)\}-1] \quad (2\text{-}2)$$

In the present paper, we will use this model for solar arrays. This photovoltaic power system provides the electric power for the load plus energy storage system such as the SMES. The solar battery circuit system is illustrated in Fig.2. We note that R is considered as the load and the parallel circuit of r and R is regarded as the SMES.

Let u(t), I(t), and x(t) be input voltage, current across the load R, and current across the super conducting magnetic coil with the inductance L in Fig.2. It is seen from Fig.2 and caluculations that the dynamics of the solar cells is represented by

$$\dot{x}(t)=Fx(t)+Gu(t), \quad (2\text{-}3a)$$
$$x(0)=0(I.C.), \quad (2\text{-}3b)$$

where

$$F=-Rr/\{L(R+r)\},\ G=r/\{L(R+r)\}, \quad (2\text{-}4)$$

and 'I.C.' denotes initial condition.

In the present paper, we will discuss how to regulate stably the above photovoltatic energy storage system which consists of the SMES. We deal with two types of control laws as the regulation method.

(1) One is the design of the optimal controller mimimizing the total energy consumed in the resistances R and r during the time interval from 0 to C, viz., the optimal controller maximizing the energy stored in the superconducting magnetic coil(Design of Optimal Controller)[5]-[6].

(2) The other is the design of the weighted one-step ahead controllers that minimize the squares error between the desired output and the predicted output plus squared value of control. In other words, the weighted minimum prediction error controllers are designed for bringing the value of energy stored in the coil to a desired value in one-step (Design of Weighted Minimum Prediction Error Controllers)[7].

3. Optimal Controller

In this section, we present the algorithm of the optimal controller for the photovoltaic energy storage system. Let the cost function I_1 be given by the sum W of the energy W_R and W_r consumed in R and r, respectively,

$$I_1=W=W_R+W_r, \quad (3\text{-}1)$$

where

$$W_R=\int_0^c RI^2(t)dt, \quad (3\text{-}2)$$

$$W_r=\int_0^c r(I(t)-x(t))^2dt. \quad (3\text{-}3)$$

We note that the current I(t) flows across the resistance R and the current x(t) flows across the reactance L in Fig.2. Expression (3.1) is rewritten in the form given by

$$I_1=(1/2)K \int_0^c L(x,u)dt, \quad (3\text{-}4a)$$

where

$$L(x,u)=r[x+(u/r)]^2+R[x-(u/r)]^2, \quad (3\text{-}4b)$$

$$K=Rr/(R+r)^2, \quad (3\text{-}4c)$$

The optimal control law which minimizes the cost function (3-4a) subject to the constraint given by (2-3) can be easily obtained by the maximum principle, invariant imbedding approach, Euler equation method etc.[5]-[6]. Applying the maximum principle, we have the two point boundary value problem(TPBVP) such that

$$\dot{x}=Fx-G^2(R+r)\lambda,\ x(0)=x_0(I.C.), \quad (3\text{-}5a)$$

$$\dot{\lambda}=-K\{r[x+(u/r)]+R[x-(u/r)]\}-\lambda F,$$
$$\lambda(c)=0(I.C.), \quad (3\text{-}5b)$$

The control function u(t) is given by

$$u(t)=-\lambda(t)G(R+r). \quad (3\text{-}6)$$

Using the Riccati transformation

$$\lambda=Px, \quad (3\text{-}7)$$

we have the Riccati differential equation and the initial condition given by

$$\dot{P}=P^2G^2(R+r)-K\{L[1-(GP/r)]+R[1+(GP/r)]\}-2PF, \quad (3\text{-}8a)$$
$$P(c)=0(I.C.). \quad (3\text{-}8b)$$

By integrating the above equation with zero initial condition in the backward direction of time, the optimal controller for minimizing the cost function (3-4a) can be obtained from (3-6).

4. Weighted Minimum Prediction Erorr Controllers For Linear Continuous-Time System

Although the design method of the usual weighted one-step ahead controller as the weighted minimum prediction error controller has been proposed for the linear discrete-time system[7], we extend this design method to the linear continuous-time system to derive the weighted one-step ahead controller. The energy stored in the magnetic coil equals the value of $(1/2)Lx^2$. In order to obtain the weighted one-step ahead control law that brings this value of energy to $(1/2)Lx^{*2}$ at time t+d(d: positive real value), we can select the weighted cost function as

$$I_2=(1/2)[x(t+d)-x*]^2+(1/2)\lambda\, u(t)^2, \quad (4-1)$$

where λ is the weight of the energy of the input voltage and x* is the desired current across the magnetic coil at time t+d.

In the following, at first we discuss the design problem of the usual weighted minimum perrdiction error controller (weighted one-step ahead controller) and secondly that of the stablilized weighted mimimum prediction errror controller (stabilized weigthed one-step ahead controller).

4-1 Weighted one-step ahead controller

It is easily seen that the control function u(t) which minimizes the cost function (4-1) is given by

$$u(t)=-(1/\lambda)(\phi(d)x(t)-x*)\phi(d)x_u(t), \quad (4-2)$$

where $\phi(d)$ is the transition matrix and x_u denotes the partial derivative of x with respect to u. These functions are calculated from

$$\phi(d)=\exp(Fd), \quad (4-3)$$

$$\dot{x}_u=Fx_u+G, \quad (4-4a)$$
$$x_u(0)=0(I.C.). \quad (4-4b)$$

Substituting (4-2) into (2-3a) yields

$$\dot{x}(t)=Fx(t)-(G/\lambda)(\phi(d)x(t)-x*)\phi(d) \times x_u(t), \quad (4-5a)$$
$$x(0)=0(I.C.), \quad (4-5b)$$

which enables one to calculate the function x(t). Hence, at this stage, the algorithm to calculate the weighted one-step ahead controller has been obtained and is given by (4-2)-(4-5). In other words, integrating (4-4a) and (4-5a) with their initial conditions and substituting the resulting x and x_u into (4-2), we get the weighted minimum prediction error controller.

It is worthwhile to point out the relationship between the optimal controller and the weighted one-step ahead controller. Rewriting (3-4a) and (4-1) as

$$I_1=(1/2)\int_0^c \{[rR/(R+r)]x^2(\tau)+[1/(R+r)]u^2(\tau)\}d\tau, \quad (4-6)$$

$$I_2=(1/2)\int_0^c \{(x(\tau)-x*)^2\delta(t+d-\tau)+u^2(\tau)\lambda\,\delta(t-\tau)\}d\tau, \quad (4-7)$$

respectively, we notice that the equation equating x*=0 in (4-7) consists with (4-6) by corresponding the weights Rr/(R+r) and 1/(R+r) in (4-6) to the weights $\delta(t+d-\tau)$ and $\lambda\,\delta(t-\tau)$ in (4-7), respectively.

4-2 Stabilized weighted one-step ahead controller

In this section, we consider the case where the stabilizer is added in front of the load and the SMES as shown in Fig.3. Using the control $\bar{u}$ which is the input to the stabilizer and produces the control u, we use the cost function I_3 instead of I_2 as

$$I_3(t+d)=(1/2)(x(t+d)-x*)^2(1/2)\lambda\,\bar{u}^2(t) \quad (4-8)$$

where

$$u(t)=[P(s)/R(s)]\bar{u}(t) \quad (4-9)$$

and the ratio [P(s)/R(s)] of the polynomials in s represents the stabilizer's dynamics.

Let the two polynomials be given by

$$P(s)=1+p_1s+\ldots+p_ms^m, \quad (4-10a)$$

$$R(s)=1+r_1s+\ldots+r_ms^m, \quad (4-10b)$$

where m is an integer. Minimizing the cost function (4-8) with respect to u(t) yields

$$u(t)=-(1/\lambda)(\phi(d)x(t)-x*)x_u(t)+P*(s)\bar{u}(t)-R*(s)\dot{u}(t), \quad (4-11)$$

where

$$P*(s)=(P(s)-1)s^{-1}, \quad (4-12a)$$

$$R*(s)=(R(s)-1)s^{-1}. \quad (4-12b)$$

The control function u given by (4-11) results in the weighted minimum prediction error controller desired.

As the simplest case, we discuss the case where P(s) is the first order polynomial and R(s) is the constant, namely,

$$P(s)=1+p_1s, \quad (4-13a)$$

$$R(s)=1. \quad (4-13b)$$

For this case, the stabilizer becomes the phase-lead circuit. Substituting the above polynomials into (4-9) and (4-11), we have

$$u(t)=\bar{u}(t)+p_1\dot{\bar{u}}(t), \quad (4-14)$$

$$u(t)=-(1/\lambda)(\phi(d)x(t)-x*)x_u+p_1\dot{\bar{u}}(t), \quad (4-15)$$

respectively. Comparing (4-15) with (4-14) yields

$$\bar{u}(t)=-(1/\lambda)(\phi(d)x(t)-x*)x_u. \quad (4-16)$$

Differentiate (4-16) with respect to t to obtain

$$\dot{\bar{u}}(t)=-(1/\lambda)[(\phi(d)\dot{x}(t)-\dot{x}*)x_u+(\phi(d)x(t)-x*)x_u]. \quad (4-17)$$

Substituting (4-17) into (4-15), we have the control law minimizing the cost function I_3 as follows:

$$u(t)=-p_1[\phi(d)Fxx_u+(\phi(d)x(t)-x^*)(Fx_u+G) +(1/p_1)(\phi(d)x(t)-x^*)x_u] \times[\lambda+p_1\phi(d)Gx_u]^{-1} \quad (4-18)$$

The corresponding x(t) is calculated from (2-3) where the control function u(t) is given by (4-18), namely,

$$\dot{x}(t)=Fx-p_1G[\phi(d)Fxx_u+(\phi(d)x(t)-x^*)(Fx_u+G)+(1/p_1)(\phi(d)x(t)-x^*)x_u] \times[\lambda+p_1\phi d)Gx_u]^{-1}. \quad (4-19)$$

Also, the control function u(t) which is the input to the stabilizer is specified by (4-16).

At this stage, all necessary equations to calculate the weighted one-step ahead controller have been obtained. It is calculated from integrating the pair of differential equations given by (4-19) and (4-4) with their initial conditions. The functions u(t) and $\bar{u}(t)$ are obtained from (4-18) and (4-16), respectively.

5. Simulation Study

The numericsl simulation study for the optimal controller is presented firstly and then that for both the weighted one-step ahead controller and the stabilized one follows.

5-1 Example 1(Optimal Controller)

The values used for the simulation study are

$$R=2.0,\ r=3.0,\ L=2.0. \quad (5-1)$$

From (2-4) and (3-4c), we see that F=0.6, G=0.3, and K=0.24. Fig.4a shows the solution P(t) for the Riccati differential equation when P(400)=0.0 is used as the initial condition. Fig.4b and Fig.4c show the corresponding current x(t) and input voltage u(t), respectively, when the initial condition x(0) is changed as x(0)=2.0, 4.0, and 6.0.

5-2 Example 2(Weighted One-Step Ahead Controller)

For this case, we used the same values as in Example 5-1 for R, r, and L. In addition, we used that

$$x^*=1.0,\ d=0.001. \quad (5-2)$$

The weighted one-step ahead control law is calculated from integrating (4-4a) and (4-5a) with their initial conditions and substituting the values x and x_u obtained into (4-2). Figs.5-a, 5-b and 5-c show the sensitivity function x_u, the state (current) x, and the weighted one-step ahead control(input voltage) u, respectively, when λ=0.005.

5-3 Example 3(Stabilized Weighted One-Step Ahead Controller)

In this example, the values used in the simulation study again are the same as those in Examples 1 and 2 except for the value of p_1. The results obtained from the simulation study are illustrated in Figs.6 when p_1 was changed. Figs.6a, 6b, 6c, and 6d show the outputs of x_u, x, u, and u when p_1 was changed. We see from Fig.6b that the transient response characteristics of the system is improved by choosing p_1 large.

6. Conclusion

In this paper, the preliminary simulation study for control problems in the photovoltaic energy storage system with the SMES was considered. Two types of controllers were presented for regulating the input voltage in the photovoltaic system. One was the conventional optimal controller maximizing the energy stored in the super conducting magnetic coil. The others were the continuous-time weighted miminum prediction error controller and its stabilized version which are the extensions of the algorithms developed for discrete-time systems[7].

Simulated results were presented for each controller by using micrcomputers. It is concluded that the results obtained in this paper provide us with the preliminary information necessary for controlling the real experimental photovoltaic energy storage system.

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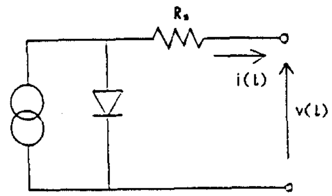

Fig.1 Equivalent circuit of solar battery

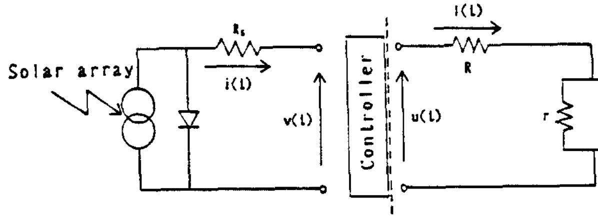

Fig.2 Photovoltaic energy storage system

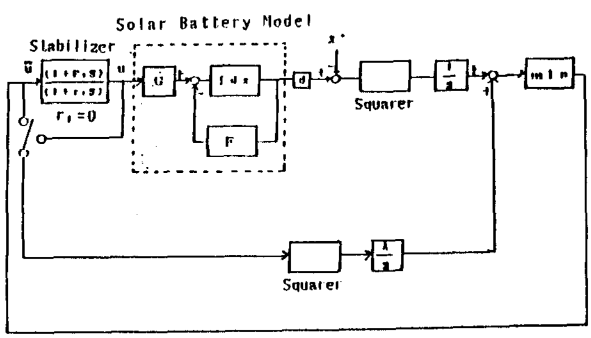

Fig.3 Configulation of stabilized weighted one-step controller

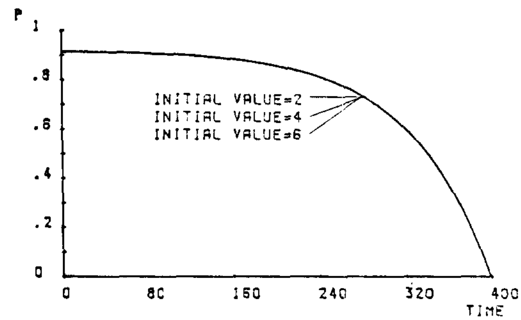

Fig.4a Outputs of P(t) when initial condition or value x(0) is changed as 2.0, 4.0, and 6.0 for Example 1

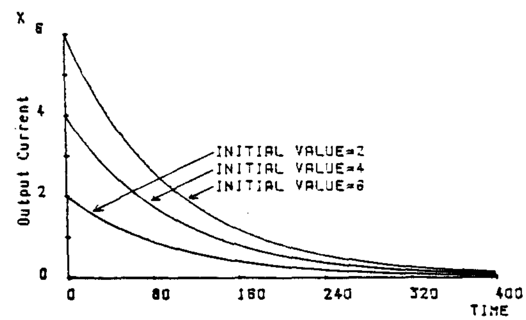

Fig.4b Corresponding states(output currents) x(t)

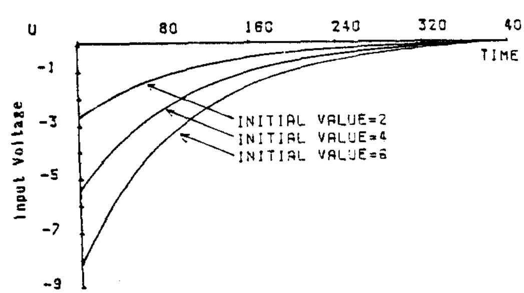

Fig.4c Corresponding optimal controls (input voltages) u(t)

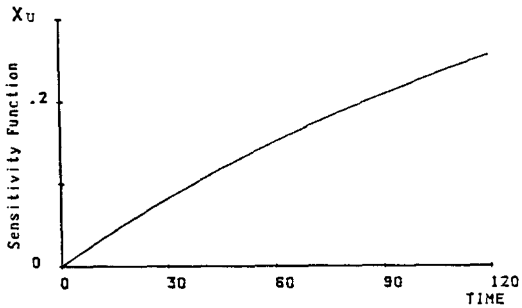

Fig.5a Output of sensitivity function $x_u(t)$ when λ =0.005 for Example 2

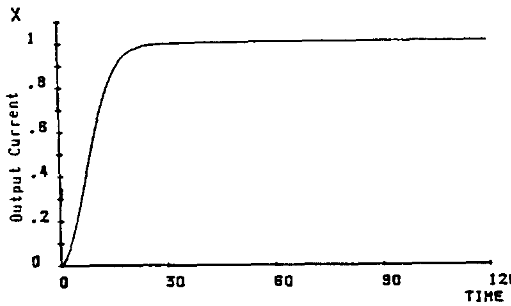

Fig.5b Corresponding state x(t)

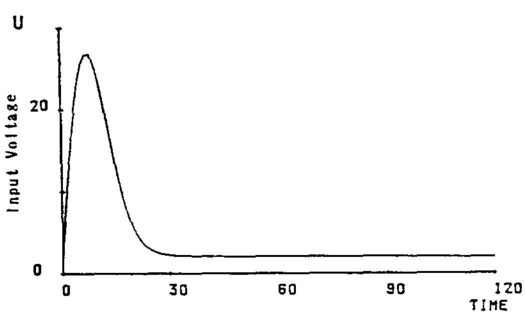

Fig.5c Corresponding weighted one-step ahead control u(t)

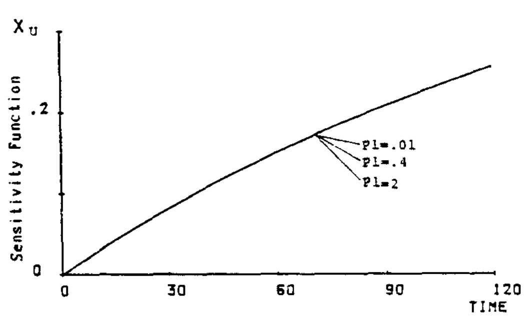

Fig.6a Outputs of sensitivity function $x_u(t)$ when p_1 is changed as 0.01, 0.4, and 2.0 for Example 3

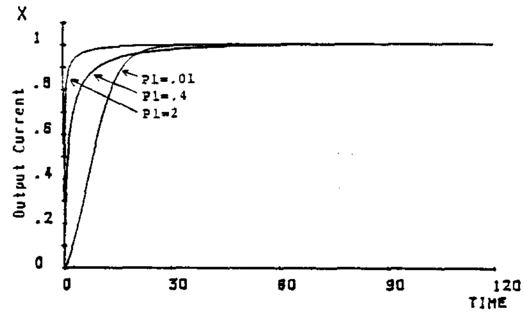

Fig.6b Corresponding states x(t)

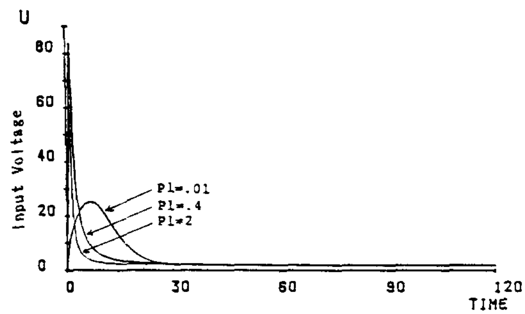

Fig.6c Corresponding stabilized weighted one-step ahead controls u(t)

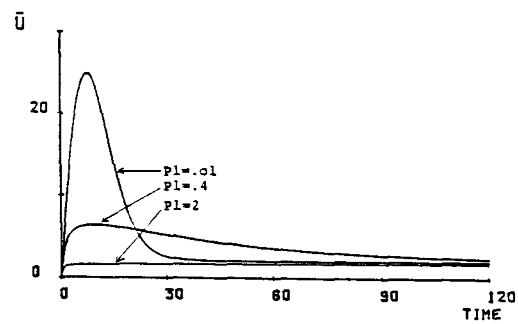

Fig.6d Corresponding controls $\bar{u}(t)$