Journal of Power Sources 112 (2002) 49–53

JOURNAL OF POWER SOURCES

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A battery ageing model used in stand alone PV systems

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Received 17 January 2002; received in revised form 15 May 2002; accepted 27 May 2002

Abstract

The authors present a new model for the ageing of a lead-acid battery which is based on the initial model of Shepherd. The proposed model allows to predict temporal variations of the Shepherd coefficients and to control the deterioration of the battery parameters and performances. The model validation has been realised by the recursive least square (RLS) algorithm by using long-term measurements under several solicitations. This study will improve the storage section of stand-alone photovoltaic systems and reduce overloads and deep discharges.

Keywords: Shepherd model; Recursive least square algorithm; Less battery storage system

1. Introduction

The electrochemical storage section constitute the weak point of photovoltaic stand alone PV plants due to their maintenance, life period and breakdowns. Thus, the improving and the conception of new storage strategies constitute a promising research area of PV applications.

In fact, we have presented in a previous study [1] two alternatives of PV systems. The first one is the less battery storage system (LBSS) in which the electrical storage is substituted by hydraulic, thermal, eutectic or latent storage. Among its main applications, we can note PV pumping, desalination and refrigeration. These plants, which work to the thread of the sun, require more favourable climatic conditions and high efficiency of dc–dc and dc–ac converters.

The second PV system is the battery storage system which uses a lead-acid battery, a dc–dc converter and a fixed frequency self commutated inverter. These systems, which are, used in rural electrification and grid connected PV plants require optimal battery regulation and control by reducing the overloads and the high discharges.

2. The storage battery model

Thanks to their sturdiness and stability, the lead-acid batteries are the most used in rural PV electrification. Such battery is mainly characterised by the following three relations:

- the relation between the state of charge (Q) and the charging current (I) [2,3],
- the variation of the voltage (V) according to the current and the state of charge (Q),
- the capacity variation (C) in function of the current [4].

The synoptic diagram of the battery model is presented in Fig. 1.

2.1. Presentation of the battery model

The simulation model, which predicts the charge–discharge phenomena, is that proposed by Shepherd [5]. This model presents the relation between voltage, current and the battery state of charge Q as follows:

in discharge ($I < 0$):

$$U(t) = U_d - g_d \frac{It}{C} + R_d I \left[1 + \frac{M_d It}{C(1 + C_d) - It}\right] \quad (1)$$

in charge ($I > 0$):

$$U(t) = U_c - g_c \left(1 - \frac{It}{C}\right) + R_c I \left[1 + \frac{M_c It}{CC_c - It}\right] \quad (2)$$

where U is the battery output voltage, g the coefficient with characterise $\Delta U = f(Q)$, C the capacity, R the internal resistance, I the current, t the time, T the temperature, M the slope of the $U = f(t, I, Q)$ characteristic, SOC the state of charge $(1-(Q/C))$, DOD the deep of discharge (Q/C) and c, d are the indices of charge and discharge, respectively.

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PII: S0378-7753(02)00341-5

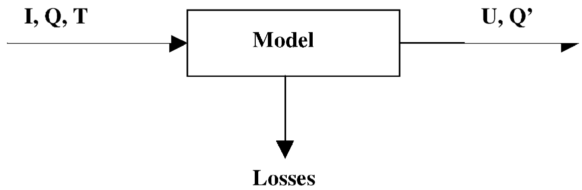

Fig. 1. Synoptic diagram of the battery model.

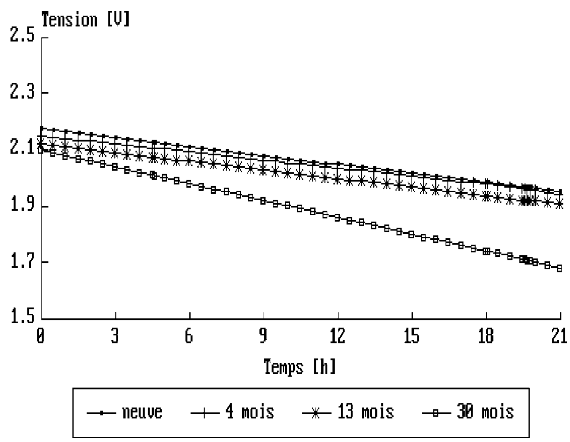

Fig. 2. Discharge characteristic $U = f(t)$ with $I = 0$ A for four states of ageing (battery ASSAD 12 V/90 Ah).

2.2. Experimental tests and results

To validate the model of Shepherd, we have proceeded experimentally to the tests of charge and discharge of the battery with fixed currents. The measured values enabled us to determine the model parameters (G_d, R_d, M_d, C_d, C_c, g_c, R_c, M_c, C_c) relating to discharge and charge processes [6].

The two parameters U_d and G_d are calculated according to the measured linear characteristic $U = f(t)$ obtained for $I = 0$ and 4.5 A (Figs. 2 and 3). The discharge resistance R_d is obtained for the origin value ($t = 0$), as:

$$R_d = [U(I = 0) - U(I \neq 0)]I^{-1} \quad (3)$$

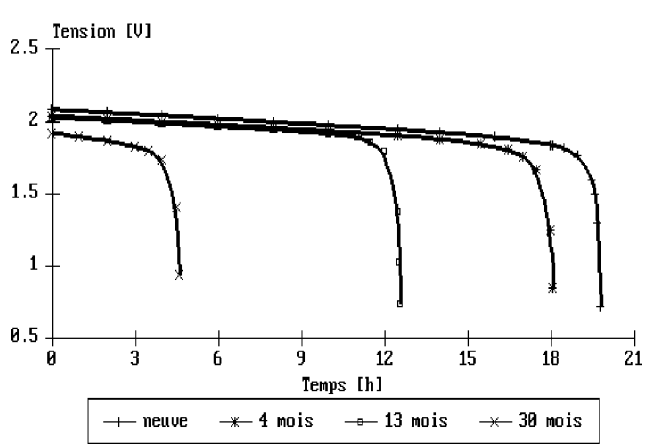

Fig. 3. Discharge variation $U = f(t)$ with $I = 4.5$ A for four states of ageing (battery ASSAD 12 V/90 Ah).

Table 1
Experimental values of the Shepherd model parameters relatives to discharge and charge of the battery ASSAD 12 V/90 Ah (new state)

Parameters	Values
U_d (V)	2.175
g_d (V)	0.21
R_d (Ω)	0.0053
M_d	0.065
C_d	−0.005
U_c (V)	2.205
g_c (V)	0.25
R_c (Ω)	0.011
M_c	0.55
C_c	1.15

The parameters C_d and M_d can be deduced with the choice of experimental points. The model parameters of the charge process are computed with the same method.

These parameters are deduced from empirical expressions obtained from a Tunisian battery, type ASSAD/TV90 (12 V/ 90 Ah) which is the most used in the photovoltaic applications in Tunisia (such as PV electrification, pumping, refrigeration, ...). The measured values of the Shepherd parameters relatives to a battery element are presented in the following Table 1.

3. Modelling of the battery ageing

The main reasons for the ageing process are the corrosion of the positive grid, the degradation of the active material and the sulfatation during long periods in low states of charge [6]. These procedures increase the internal resistance, decrease the capacity and reduce the battery life period. However, the Shepherd model given by expressions (1) and (2) does not represent the ageing of the main parameters in function of the time. In order to take into account the dynamic behaviour of the battery, we will identify the temporal model of each parameter by using experimental input/output measurements under several solicitations ($I = 0$, 1, 4.5 A, ...) and state of charge Q (new, 1 month old, 3 months old, 1 year old, ...).

3.1. Procedure and experimental results

From the measured results, we have calculated the parameters values of the Shepherd model for each state of ageing. As application, we have operated tests of charge and discharge to the same type of the battery ASSAD 12 V/ 90 Ah for four various states of its ageing: new, 4, 13 and 30 months old.

The obtained curves are presented by the Figs. 2–4 for the discharge and Figs. 5–7 for the charge. Table 2 represents the values of the same parameters for the other states of ageing.

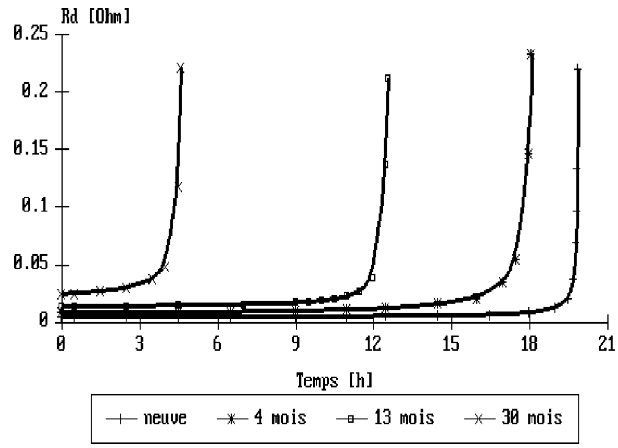

Fig. 4. Variation of discharge resistance $R_d = f(t)$ for four states of ageing (battery ASSAD 12 V/90 Ah).

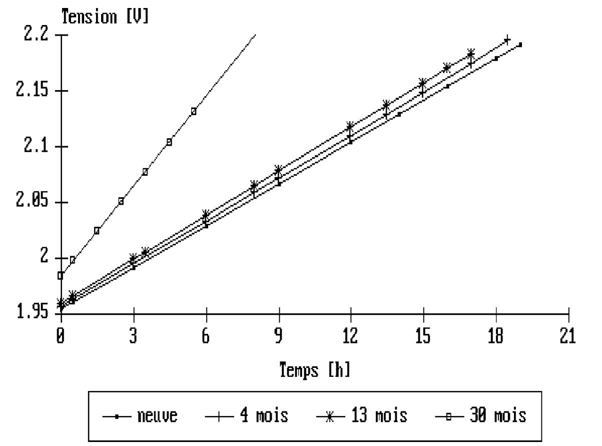

Fig. 5. Charge characteristic $U = f(t)$ with $I = 0$ A for four states of ageing (battery ASSAD 12 V/90 Ah).

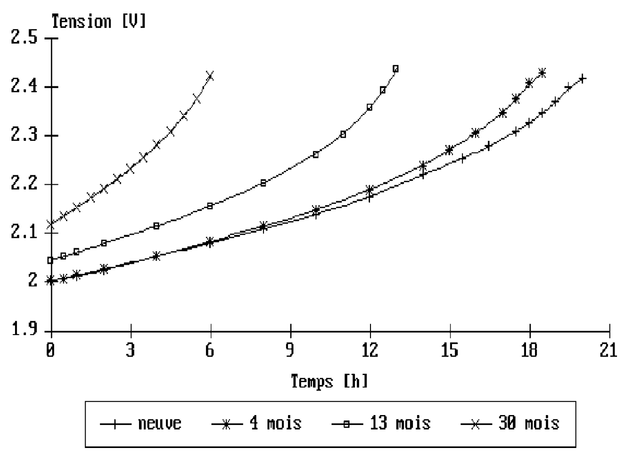

Fig. 6. Charge variation $U = f(t)$ with $I = 4.5$ A for four states of ageing (battery ASSAD 12 V/90 Ah).

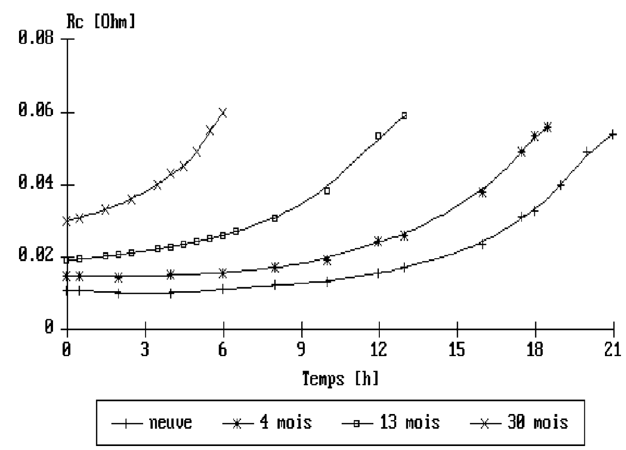

Fig. 7. Variation of the charge resistance $R_c = f(t)$ for four states of ageing (battery ASSAD12 V/90 Ah).

3.2. Presentation of the model of ageing

Thus, the obtained model of ageing is the following [6]: in discharge:

$$U = U_d - g_d \frac{It}{C} + R_d I \left[1 + \frac{M_d It}{C(1 + C_d) - It}\right] \quad (4a)$$

$$C_d = -0.005 - 0.0012t \quad (4b)$$

$$U_d = (2.175 - 0.0001D^2) - 0.036 \log(0.25t + 1) \quad (4c)$$

$$M_d = 0.065 + 0.011 \log(0.75t + 1) \quad (4d)$$

$$g_d = 0.210 + 0.0473 \log(0.33t + 1) \quad (4e)$$

$$R_d = (0.0053 + 0.0008D) \left(\frac{20 - 0.5D}{\sqrt{(20 - 0.5D)^2 - t^2}} \right) \quad (4f)$$

in charge:

$$U = U_c - g_c \left(1 - \frac{It}{C}\right) + R_c I \left[1 + \frac{M_c It}{CC_c - It}\right] \quad (4a')$$

$$C_c = 1.15 + 0.0004t(t + 30) \quad (4b')$$

$$U_c = (2.01 + 0.00013D^2) + 0.0266t \log(t + 1) \quad (4c')$$

$$M_c = 0.55 + 0.053 \log(0.25t + 1) \quad (4d')$$

$$g_c = 0.250 - 0.078 \log(0.125t + 1) \quad (4e')$$

$$R_c = (0.011 + 0.001D) \exp\left(\frac{-t}{t - 20 + 0.5D}\right) \quad (4f')$$

where D is the battery age (in months), t the time variable (in hours). The values at origin ($t = 0$) indicate the new state of the battery.

3.3. The life time reduction

The lifetime reduction depends on the daily cycles, the deep of discharge, the sulfatation and corrosion process. Hence, the lifetime reduction due to sulfatation can be expressed by the empirical expression [7]:

$$X_s(C) = 0.6 + 0.1C \quad (5)$$

Table 2
Effect of the ageing on the battery parameters (battery ASSAD 12 V/90 Ah)

Months	U_d (V)	g_d (V)	R_d (Ω)	M_d	C_d	U_c (V)	g_c (V)	R_c (Ω)	M_c	C_c
4	2.15	0.170	0.008	0.080	−0.01	2.167	0.23	0.014	0.58	1.17
13	2.12	0.130	0.014	0.092	−0.02	2.130	0.17	0.019	0.62	1.25
30	2.10	0.097	0.025	0.100	−0.04	2.115	0.13	0.030	0.65	1.80

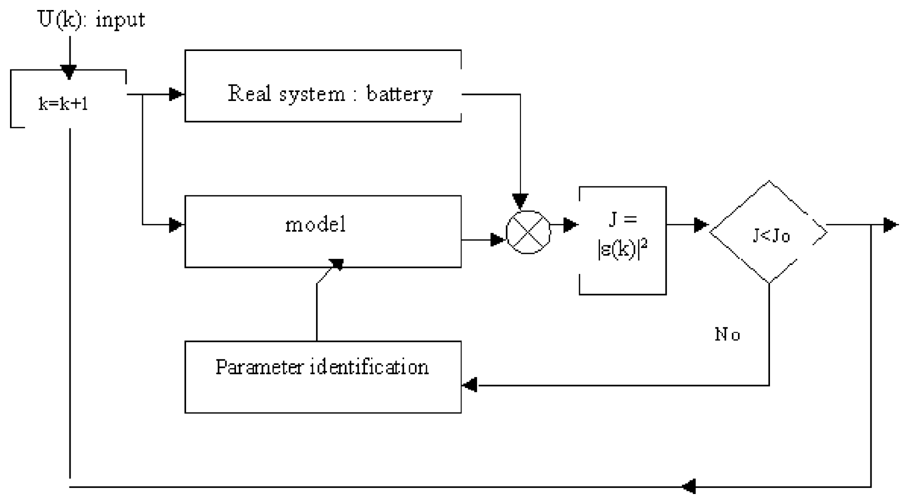

Fig. 8. The validation algorithm.

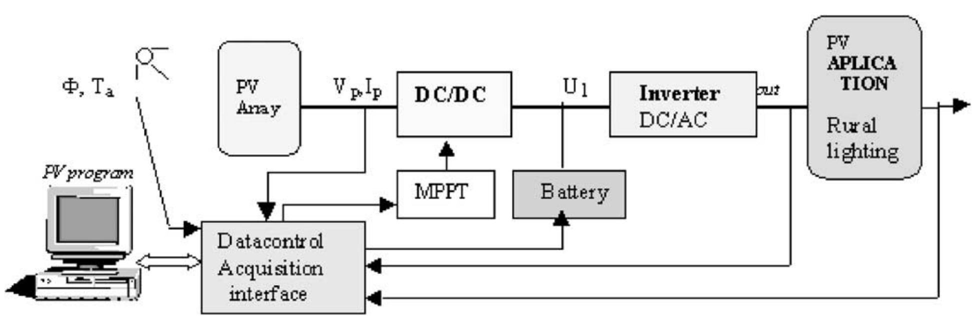

Fig. 9. Configuration of a photovoltaic plant.

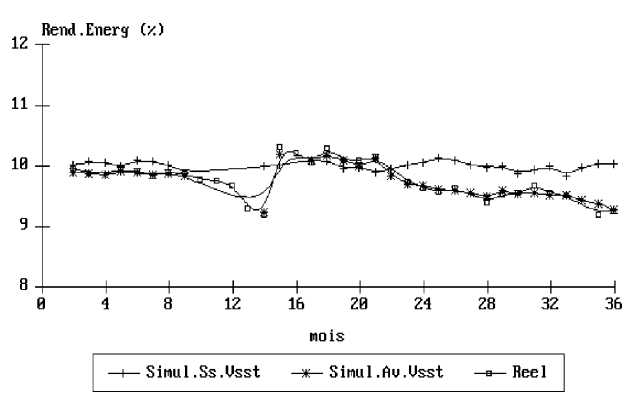

Fig. 10. Comparison between measured and simulated energetic efficiency (with and without battery ageing PV 55 Wcr, $B = 90$ Ah).

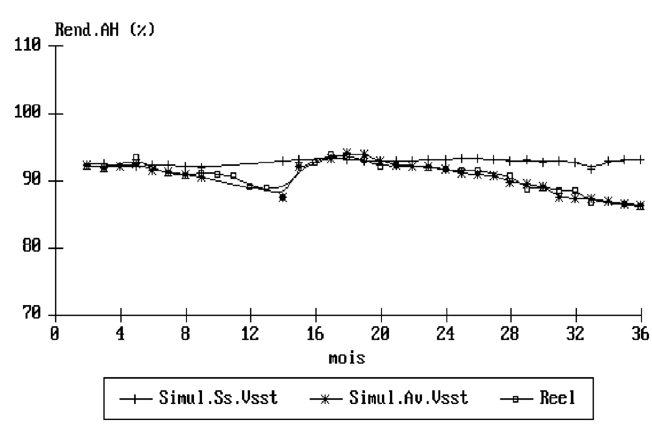

Fig. 11. Comparison between measured and simulated Ah efficiency (with and without battery ageing PV 55 Wcr, $B = 90$ Ah).

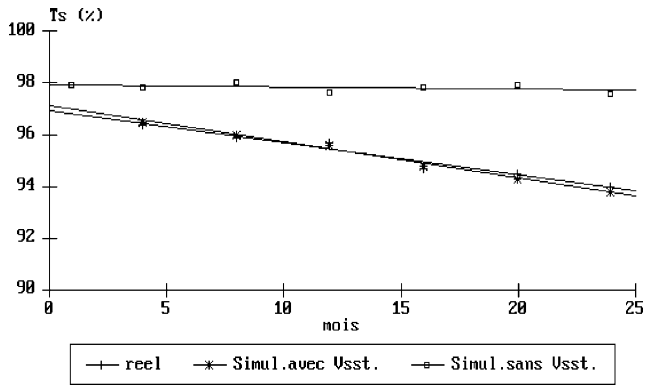

Fig. 12. Comparison between measured and simulated satisfaction rate (with and without battery ageing PV 55 Wcr, $B = 90$ Ah).

Yet, the life period resulting from corrosion is:

$$X_c(C) = 0.88 + 13.3C^{-3.4} \quad (6)$$

The battery capacity for a discharge current (I) can be given by:

$$C(I) = C_0\left(\frac{1.66}{1 + 0.66(I/I_0)^{0.9}}\right)(1 + 0.005\Delta T) \quad (7)$$

where $\Delta T = T_b - T_a$ (battery cell temperature−ambient temperature) and $I_0 = 4.5$ A (discharge current with remarkable solicitation) (DOD = 80%).

3.4. Results

The capacity of the battery is the most sensitive parameter to ageing since its slope is raised and remarkable. The other parameters U_d, G_d, U_c, g_c, R_d and R_c decrease according to logarithmic, exponential and linear laws. C_c and C_d have an influence on the speed of the end of charge and discharge processes, respectively.

4. Validation

To validate the model of the battery ageing, we have used the recursive least square algorithm of Fig. 8 which was integrated in the software environment (INSEL [8]). The experimental and simulated values are compared in order to minimise the quadratic error [9]. Besides we have compared in Figs. 9–11 the measured and simulated efficiency and satisfaction rate of a domestic PV rural electrification system.

This hardware platform which is illustrated by Fig. 9 is constituted by:

- a domestic PV electrification system fed by a 55 power peak panel, a 90 Ah battery and a load of 350 WH per day (lighting 20 W + TV30 W);
- a data acquisition system MODAS (16 inputs) which collect the experimental voltages, currents, efficiencies, temperatures, solar radiation, ...

For example, we presented in the Figs. 11 and 12 the experimental and simulated variation of the satisfaction rate and the energetic efficiency. These parameters were simulated by considering two cases of the battery behaviour with ageing and without ageing.

We can observe how the ageing factor affects not only the battery parameters but also the PV system performances especially the satisfaction rate.

5. Conclusion

In this paper, we have identified the temporal model of a lead-acid battery. Moreover, we demonstrated how the battery ageing affects all parameters of the Shepherd model. This variation is most remarkable with dynamic solicitations (in current and load consumption). However, in nominal functioning conditions, the ageing affects slightly the output voltage and is not significant before the first year.

To protect the battery from deep discharges and irreversible sulfatations, the load request and the power consumption must be limited and controlled. To avoid deep discharge, the voltage output must be fixed in function of the discharge current.

Finally, the battery regulator in insufficient to reduce ageing consequences and thus must be assisted by an optimal management and monitoring of the PV plant.

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