Renewable Energy Management based on Timed Hybrid Petri Net Approach for an Isolated Chalet Application

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Received: 03.07.2016- Accepted: 21.05.2016

Abstract- An energy management algorithm is proposed in order to make a best use of the renewable generation and storage units. The management strategy should guarantee a permanent production of electricity in an isolated chalet for an off-grid system supplied by photovoltaic panels and batteries. The chalet is composed by three types of loads: priority loads where they will be supplied all time, secondary load where it may be supplied only in case of energy availability and finally the extra-loads will be supplied during a definite time. This paper presents a model for isolated system behavior in terms of control powers exchanged between sources power and loads demand. The model is based on Timed Hybrid Petri Net formalism. Therefore, an iterative algorithm for power flow management satisfies requirement of each type of load based on the photovoltaic panels production and the storage units. Obtained results show that the proposed strategy satisfies the priority loads during the whole day, covers the secondary load energy and gives user liberty to exploit the extra-loads as possible.

Keywords— Management; Modelling; THPN; Priority Loads; Secondary Load; Extra_Loads; Kalmen Filter; Battaries; ANFIS; PVPs.

1. Introduction

The growing demand for electricity with the exhaustion of fossil fuel and the increasing environmental crisis encourage the investment in renewable resources. Photovoltaic generation has been extensively developed due to its sustainable, eco-friendly properties and its relatively high efficiency. The uncertainty due to their natural fluctuations requires the use of storage so as to save the over generated energy and to supply the load in case of energy shortage. Hence, an energy management strategy becomes necessary for such systems to match the supplied power to demand [1, 2].

Various research works propose energy management solutions and tools for renewable energy based systems. Genetic Algorithm is usually used to solve the environmental/economic problem especially in case of nonlinear constrained optimization. The optimization aims to minimize the cost function of the emission gases, start-up costs, as well as the operation and maintenance costs [3]. As the operation cost model comprises many constraints; pragmatic constraints should be fixed in order to avoid algorithm divergence. Also, in case the experience of the user about the system behavior is defined, fuzzy logic becomes the powerful management technique [4, 5]. In fact, fuzzy logic offers a non-conventional model based on expert knowledge for nonlinear systems represented by complicated mathematical models. Among used techniques, the Petri nets (PNs) are a graphical and mathematical tool originally developed for the modeling and analysis of distributed systems and in particular for the notions of concurrence, non-determinism, communication, and synchronization [6]. The easy implementation of PN make it easy the combining with other theory. Bond graphs is also a graphical model. It is collected with PN to model the hybrid behavior for hybrid dynamic systems. This approach gives an efficient solution to the transition problematic and can study the theoretical for complexity hybrid models [7]. In other hand, several extensions are developed for PN. Timed Hybrid Petri Nets (THPNs) are the enhancement of PNs by the introduction of extensions for discrete and continuous systems management taking into account the time [8]. THPNs provided satisfactory results under informal implementation for dynamic systems [9, 10, 11].

This paper proposes an energy management algorithm for a chalet. The objective is to satisfy priority loads during the whole day and to supply secondary load as soon as energy is available and even to allow extra_loads to be supplied during a definite time. The algorithm is based on THPNs formalism. A chalet, of different types of loads (priority, secondary and extra), in an isolated area is considered as a case study. The first section estimated available energies sources. The battery state of charge estimation is determined by state space representation based on Kalman filter. As for the estimation of PVPs generation, the ANFIS technique is used. Section two focuses on the strategy of the energy management. It presents the THPNs principle and gives the algorithm implementation of the management model. Finally, section three shows the results and discussions.

2. Estimation of Sources Energies

The proposed structure of the isolated chalet (Fig. 1) is composed of ten photovoltaic panels (250Wp) connected to two lead acid batteries (SLT210) via a common DC voltage bus through DC/DC chopper. A DC/AC inverter is inserted between the DC bus and an AC bus to ensure the power supply of three different types of domestic loads: priority (refrigerator, air conditioner and lighting), secondary (washing machine) and the extra-loads. The supplied power by the sources of energies is modelled and estimated. Obtained forecasts are used by the management algorithm so as to decide the switching ON/OFF of the extra-load, to schedule the secondary load and in order to guarantee the priority loads supply.

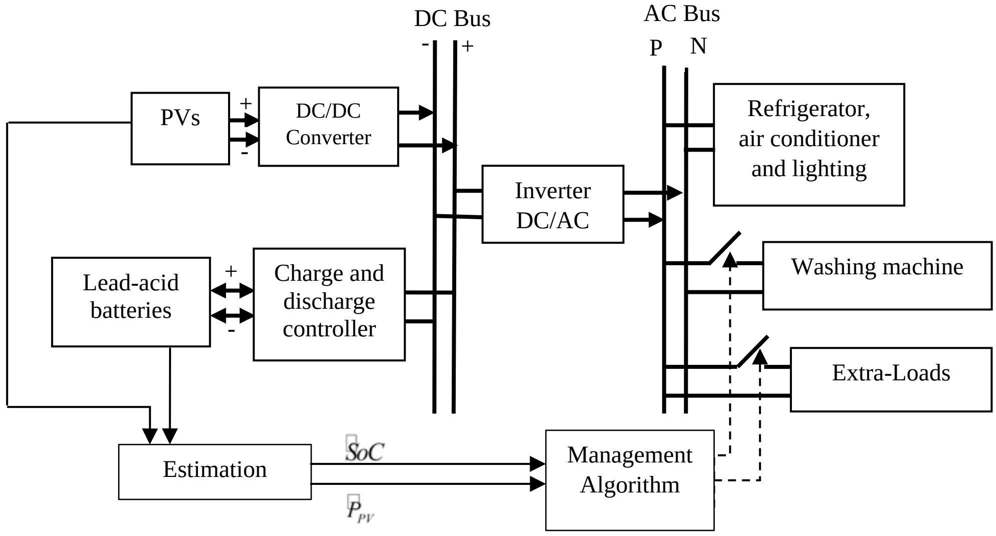


Fig. 1. Structure of isolated chalet

2.1. Storage energy estimation

The estimation of stored energy is based on calculation of its state of charge (SoC). Accordingly, Figure 2 shows the electric equivalent circuit of the lead-acid battery that allows a dynamic and accurate determination of the (SoC) [12].

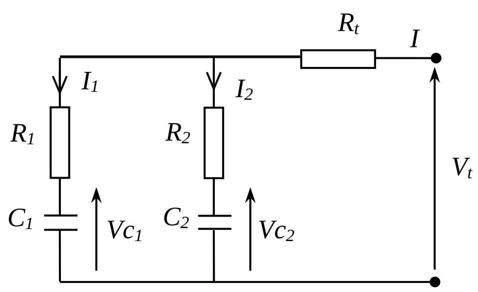


Fig. 2. Equivalent electrical circuit of the battery

By applying the law of meshes on the equivalent circuit of the battery we can determine the expressions of voltages model function of different parameters of this model. So, we can expressed a state-space model based on the voltages expressions. In a previous published work [12], the state space representation given by Eq.1 was established and validated on the basis of the battery equivalent circuit:

$$\begin{cases} \begin{bmatrix} \dot{V}_{C1} \\ \dot{V}_{C2} \\ \dot{V}_t \end{bmatrix} = \begin{bmatrix} -\frac{1}{C_1(R_1+R_2)} & \frac{1}{C_1(R_1+R_2)} & 0 \\ \frac{1}{C_2(R_1+R_2)} & -\frac{1}{C_2(R_1+R_2)} & 0 \\ A(3,1) & 0 & A(3,3) \end{bmatrix} \begin{bmatrix} V_{C1} \\ V_{C2} \\ V_t \end{bmatrix} + \begin{bmatrix} \frac{R_s}{C_1(R_1+R_2)} \\ \frac{R_e}{C_2(R_1+R_2)} \\ B(3,1) \end{bmatrix} I \\ Y = [001] \begin{bmatrix} V_{C1} \\ V_{C2} \\ V_t \end{bmatrix} + 0.I \end{cases} \quad (1)$$

where:

$$A(3,1) = -\frac{R_2}{C_1.(R_1+R_2)^2} + \frac{R_1}{C_2.(R_1+R_2)^2} - \frac{R_2{}^2}{C_1.R_1.(R_1+R_2)^2} + \frac{R_2}{C_2(R_1+R_2)^2}$$

$$A(3,3)=\frac{R_2}{C_1.R_1.(R_1+R_2)}-\frac{1}{C_2.(R_1+R_2)}$$

$$B(3,1)=\frac{R_1^{\,2}}{C_2.(R_1+R_2)^2}-\frac{R_2.R_t}{C_1.(R_1+R_2)}-\frac{R_t}{C_2.(R_1+R_2)}+\frac{R_1.R_2}{C_2(R_1+R_2)^2}$$

$X(t)=\begin{bmatrix} V_{C1}(t) \\ V_{C2}(t) \\ V_t(t) \end{bmatrix}$ is the state vector, $V_t(t)$ is the output and $I(\mathrm{t})$ is the input.

The discretization of the state-space representation leads to the implementation of Kalman filter (KF) which allows the estimation of SoC. KF provides the best estimation of the state vector X_k, on the basis of the observations up to a given time steps by minimizing the variance criterion as follows:

$$\mathrm{Min}\{\mathrm{E}\,(\left[X_k-\hat{X}_{k/k}\right].\left[X_k-\hat{X}_{k/k}\right]^{\mathrm{T}})\} \qquad (2)$$

Consequently, the estimated SoC is given by (3) where it is expressed function of the parameters of electrical model of the lead acid battery [12]:

$$\hat{S}oC=\frac{1}{E_0-E_1}\begin{bmatrix}\frac{R_2}{R_1+R_2} & \frac{R_1}{R_1+R_2}\end{bmatrix}\begin{bmatrix}\hat{V}_{C1} \\ \hat{V}_{C2}\end{bmatrix}-\frac{n.E_1}{E_0-E_1} \qquad (3)$$

Where:

E_0 =2.17 V is the unloaded voltage of a cell.

E_1 =1.75 V is the limit discharge voltage of a cell.

R_1=R_2= 0.0168 Ω are two resistances of the battery model where their values are determined from experimental tests on solar battery ASSAD SLT210 (Table 1).

Thus, the usable energy in the battery is determined by [13]:

$$\hat{E}_{UBAT}=C.V_{BAT}.(1-\hat{S}oC) \qquad (4)$$

2.2. Estimation of the photovoltaic generation

The daily photovoltaic energy generation is calculated by the estimated solar radiation and ambient temperature for a day *'d'*. Equation (5) and (6) give respectively the distributions of the solar radiation and the ambient temperature. The time *'t'* is counted since sunrise for the considered day *'d'* [13].

$$\hat{I}(d,t)=\frac{\pi\hat{G}(d)}{2DL(d)}\sin(\frac{\pi t}{DL(d)}) \qquad (5)$$

$$\hat{T}_a(d,t)=\frac{\hat{T}_{\max}(d)+\hat{T}_{\min}(d)}{2}+\frac{\hat{T}_{\max}(d)-\hat{T}_{\min}(d)}{2}\sin(\frac{\pi(t-1)}{12}) \qquad (6)$$

Where G , T_{max} and T_{min} are respectively the daily global solar radiation, the maximum and minimum Temperature. These parameters are estimated using ANFIS technique (Adaptive Network Fuzzy Inference System). This method is a class of adaptive networks that is functionally equivalent to fuzzy inference systems. It is used in the prediction of nonlinear stochastic quantities [14]. The basic principle of the ANFIS technique is to exploit the past measurements taken on the system to predict the future sample. So, the estimated daily photovoltaic energy generation is expressed by (7) in standard conditions where the irradiance G=1000 W/m2 and the ambient temperature T=25 °C.

$$\hat{P}_{pv}=(3.33+1.2\times10^{-3}\left(\frac{\hat{I}(d,t)}{1000}\right)\left(\hat{T}_a(d,t)+\frac{\hat{I}(d,t)}{40}-25\right)+3.35(\frac{\hat{I}(d,t)}{1000}-1))V_{pv} \qquad (7)$$

Where the PVP voltage fixed to 12 V.

3. Energy Management Algorithm

After the estimation of energy parameters of installation according to the climatic effect, several goals could be set to ensure the best energy management. To achieve this, it is important to highlight the main key characteristics of proposed strategy. The principal items are as follow:

- There will be income if the PVPs power is greater than the loads demand and SoC of batteries is less than 100%.
- Ensure functioning of priority loads (the refrigerator, the air conditioner and the lighting) which we cannot abandoned them in our chalet in summer season.
- Optimal scheduling for the secondary load where its start time is depending on availability of energy.
- Operate the extra_loads only during a definite time in the day. This gives to resident the liberty to exploit the surplus of energy.
- The batteries can cover the lack of energy for all types of loads whenever the PVPs power is insufficient to supply loads.

To accomplish this operation strategy, an iterative algorithm is developed in order to control and manage the power flows between energy sources and the demands for each type of loads. It takes account of the estimated energy parameters and the loads profiles. This algorithm based on a model where describe the behavior of system every minute. The THPN formalism is proposed to model the isolated chalet. Fig. 3 represents a synoptic schema of the main approach.

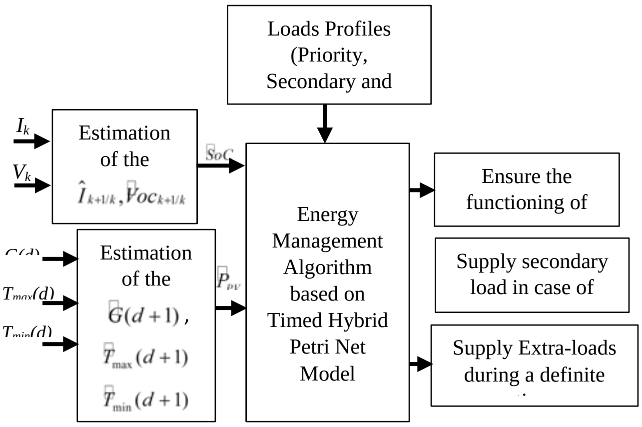


Fig. 3. The synoptic schema of the proposed work

3.1. Timed Hybrid Petri Net formalism

Several extensions of Petri Net formalism have been proposed for analysis and modelling of systems [8, 9]. In this case study, the THPN was adopted. It is described as 6-tuples [15], THPN= {P, T, A, W, M0, D}, where:

• P is a non-empty finite set of places. It is partitioned into two subsets, one of continuous places Pc and the other of discrete places Pd.

• T is a non-empty finite set of transitions constituted by two subsets, one present the immediate transitions Ti and the second present the delay transitions Tdl.

• A is a set of arcs, A ⊆ (P×T)∪(T × P) which consists of a set Ao of ordinary arcs, a set AT of testing arcs and a set Ai of inhibitor arcs.

• W refers to arc multiplicity weights. It is a weight function. It can be a mathematical function, a function of certain places 'markings or a constant number.

• M0 is the initial marking, which represents the initial number of tokens in places.

• Finally, D is a set of transition delays associating each transition Tdl with a delay function. This delay function determines for how long the transition must wait before it is allowed to fire.

These sets are gathered to define the THPN graph. Table 1 give the main symbols definitions.

Table1. Standard symbols of THPN graph

Symbol	Definition
○	The discrete places are drawn as simple circle
◎	The continuous places are drawn as double circles
▬	The discrete transitions are represented by a black rectangle
▭	The continuous transitions are represented by an empty rectangle
⟶	The ordinary arcs are depict by usual arcs
—o	The inhibitor arcs are depict by arcs whose end is marked with a small circle
- - ▸	The test arcs are represented with a discontinuous arrow

If a place 'p' and a transition 't' are connected with an ordinary arc with weight w, 't' can be fired if the marking of 'p' is greater than or equal to w. On the contrary, for the inhibitor arcs, the marking of 'p' should be less than w. The test arc connects continuous place with a continuous transition. In the case of structural conflicts, the priorities of firing the transitions can be presented. Therefore, the priority of a transition will be fixed in simulation.

3.2. The algorithm implementation based on THPN model

The presented methodology (Fig. 4) takes account of the daily photovoltaic energy generation (Ppv) and the available batteries power (Pbat). All types of loads can be connected to each power sources. Ppl is the priority loads powers. Psl is the secondary load power. T is the time when secondary load starts to operate. Times-Extra-loads is the times where extra_loads can operate. PLSC and SLSC indicate respectively Priority Load State Control and Secondary Load State Control. If priority or secondary loads are ready to operate, the 'Load State Control' is equal to 1 else it is equal to 0.

The implementing of system by THPN formalism uses Visual Object Net++ software. The proposed THPN model describes the model's parameters and the different conditions to switch on outputs. Each type of load is represented by four discrete places (Fig. 5) to symbolize: its states (Places: 'LiON' and 'LiOFF') and the order to change its states (Places: 'makeLiON' and 'makeLiOFF') with i ϵ {1, 2, 3}; 1 as priority loads, 2 as secondary load and 3 as extra-loads. Also, an intermediary place 'Intj' (j ϵ {1, 2, 3}) is presented to link two transitions in each load model. Finally for the priority and secondary loads, a place will be added to indicate the load state control (PLSC, SLSC). This last gives an idea for the future state of loads (Fig. 4).

Each source of energy is modeled by a continuous place to symbolize its power every minute during the day (Places: 'PPV' and 'Pbat'). The continuous place is connected to the three types of loads via a discrete transition that enables the loads switching ON. Since a load has started, it won't be stopped until its operation cycle is completed. This is ensured by the transitions T5, T13 and T19 which become respectively activated after the times: 'TimePL', 'TimeSL' and 'TimeExtL'. Transitions T11 and T17 will be fired just when time is equal of the time for start time load operation. The simulation is carried for a one minute time step during the day. The transitions T7, T14, T21 and T25 are delayed in activation for one minute. The intermediate places 'Int' and 'Int4' are used to link transitions. The unique continuous transition ('charging') ensures the batteries charging state. It is activated while the energy is available and the battery SoC is less than 100%.

Uses of the delay transitions explains the usefulness of Time in PN. Also, the matching of discrete and continuous nets justifies the hybrid term.

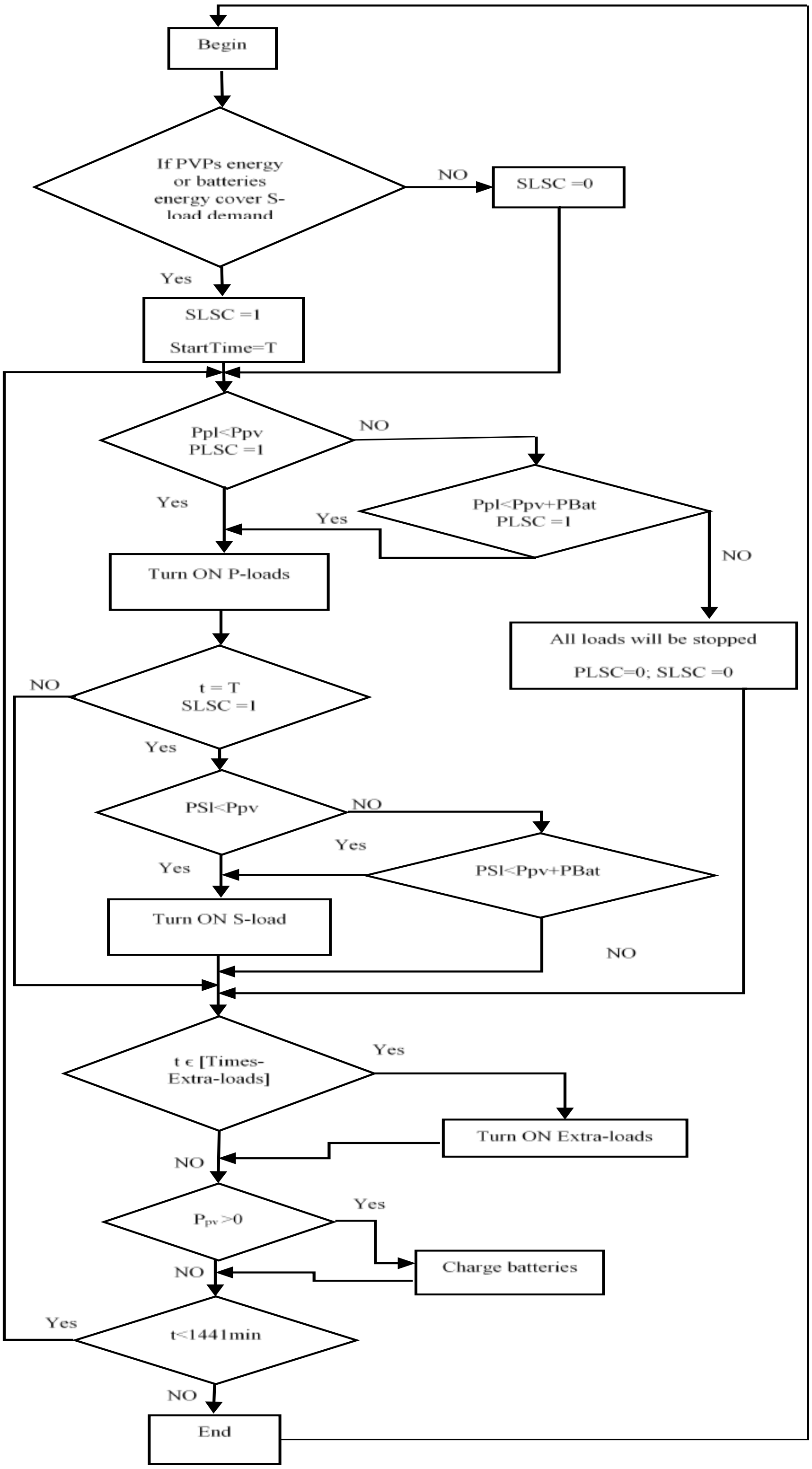
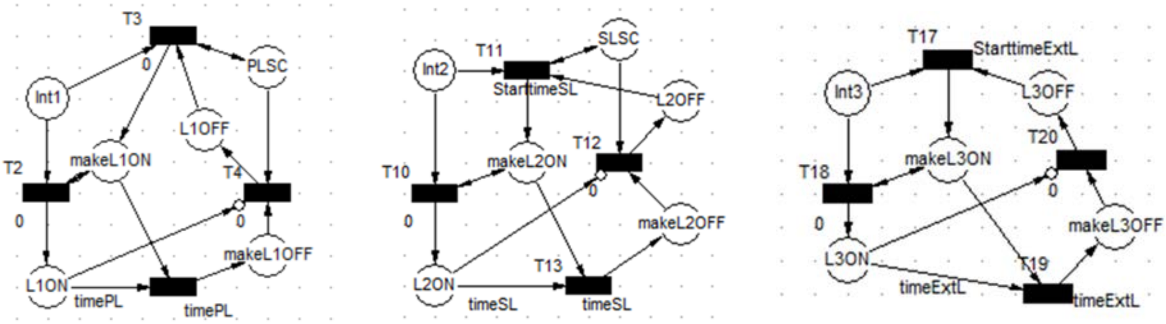


Fig. 4. Proposed *THPN* methodology

All places are represented by their type and their initial value in Table 2. Places are linked with different type of arc; each arc has a definite weight. Table 3 gives an idea for the non-unitary weight. The remainder of arcs have an unitary weight. The main advantage of THPN is the possibility to model and visualize system behavior including synchronization and management of loads.



(a) Priority Load Model (a) Secodary Load Model (c) Extra_Load Model

Fig. 5. THPN Loads Model

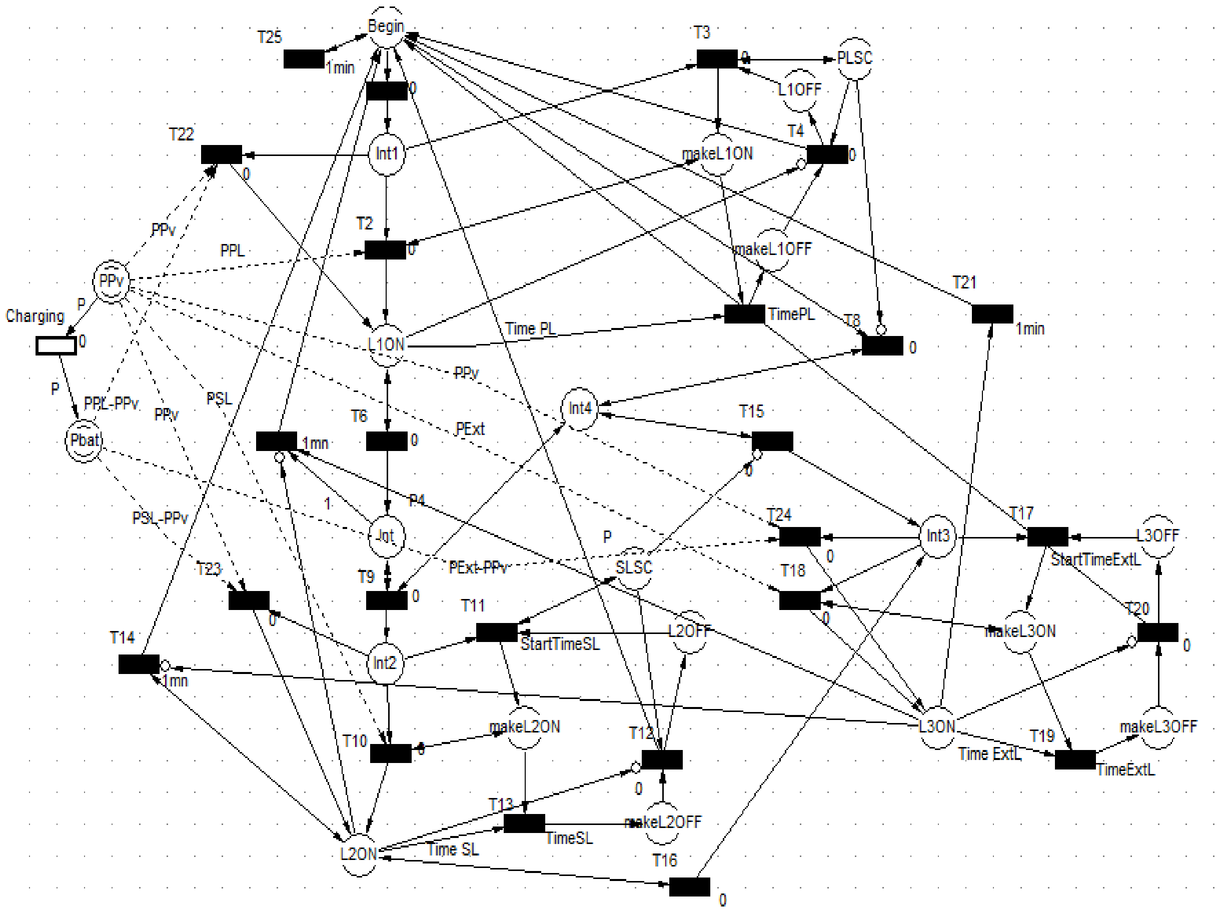


Fig.6. THPN System Model

Table 2. Description and initial values of places of THPN system model

Places	Description	Type	Initial value
Begin	Start Place	Discrete	1
PLSC	Priority Loads State Control	Discrete	0
makeL1ON	Turn ON priority Loads	Discrete	0
L1OFF	Priority loads is OFF	Discrete	1
makeL1OFF	Turn OFF priority loads	Discrete	0
L1ON	Priority loads are operating	Discrete	0
SLSC	Secondary Load State Control	Discrete	0
L2OFF	Secondary load is OFF	Discrete	1
makeL2ON	Turn ON secondary Load	Discrete	0
L2ON	Secondary load is operating	Discrete	0
makeL2OFF	Turn OFF Secondary load	Discrete	0
L3OFF	extra_loads is OFF	Discrete	1
makeL3ON	Turn ON extra_Loads	Discrete	0
L3ON	extra_Loads are operating	Discrete	0
makeL3OFF	Turn OFF extra_Loads	Discrete	0
Int	Intermediate Place	Discrete	1
Int1	Intermediate Place in priority loads model	Discrete	1
Int2	Intermediate Place in secondary load model	Discrete	1
Int3	Intermediate Place in extra_loads model	Discrete	1
Int4	Intermediate Place	Discrete	1
PPV	Photovoltaic power	continuous	Ppv
Pbat	Batteries power	continuous	PBat

Table 3. Description of non-unitary weight arcs for THPN system model

Input	Out put	Arc weight	Description of arc function
T2	PPv	PPL	PVPs provide needed power to priority loads
T22	PPv	PPv	PVPs provide all his power to priority loads
T22	Pbat	PPL-PPv	Batteries cover lack of power for priority loads
T10	PPv	PSL	PVPs provide needed power to secondary load
T23	PPv	PPv	PVPs provide all his power to secondary load
T23	Pbat	PSL-PPv	Batteries cover lack of power for secondary load
T18	PPv	PExtL	PVPs provide needed power to extra_loads
T24	PPv	PPv	PVPs provide all his power to extra_loads
T24	Pbat	PExtL-PPv	Batteries cover lack of power for extra_loads
T5	L1ON	timePL	End time priority loads operation
T13	L2ON	timeSL	End time secondary load operation
T19	L3ON	timeExtL	End time extra_loads operation
Charging	PPv	P	PVPs provide power to batteries
Charging	Pbat	P	Charge batteries of remaining power supplied by PVPs

4. Simulation Results and Discussion

The chalet is characterized by:

- Operation period: summer (June, July, August).
- Region: Sfax, Tunisia (North Africa).
- Localization parameter :
  - Latitude: 34.733
  - Longitude: 10.767
- Daily energy consumptions/load:
  - Refrigerator = 560 Wh
  - Air conditioner = 7500 Wh
  - Lighting = 450 Wh

- Washing machine = 542 Wh

- Extra_Loads = 1620 Wh

- Sources of energy:

- 5 Photovoltaic panels which produce 2500Wp

- 2 batteries with a total capacity of 420 Ah

The simulation first step consists of estimating the energy parameters of the chalet. The initial state of charge of the battery is calculated on the basis of the state space model using Kalman Filter. Fig. 5 shows the estimated values of SoC which are near to measured values in case of random discharge.

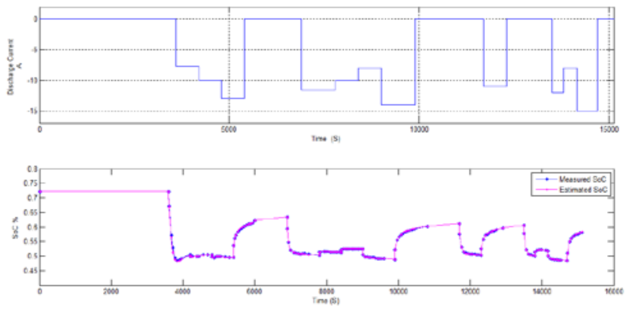


Fig. 5. State of charge of battery in response to random discharge

Thereafter, the generation is estimated for the three months considering the estimation of solar radiation and ambient temperature using ANFIS technique. The database of measured solar radiation and temperature is given by the meteorological station of Sfax, corresponding to the year 2012. July 18th is fixed as a typical day to validate the simulation. Fig. 6 shows a concordance between estimated and measured curves of the ambient temperature and solar radiation (T_a and I) and the generated PV power from sunrise to sunset.

The second simulation step consists of running the implemented THPN model. Fig. 7 presents the proposed loads profiles and the curve of lost, PVP and batteries powers. It is clear that the THPN formalism provides good results where priority loads are always satisfied during the considered day and the secondary load operation depends on available power. The operation start time of the secondary load is determined function of the energy availability as shown in Fig. 7 and the pic power of this load is covered by sources power. Extra_loads allow to resident to exploit the surplus of produced energy in a definite time.

It is noticed that batteries charging starts when estimated PVPs power is greater than the needed power for priority loads until the end of the day. Batteries are disconnected from charging to supply the priority loads in case of insufficient PVP power.

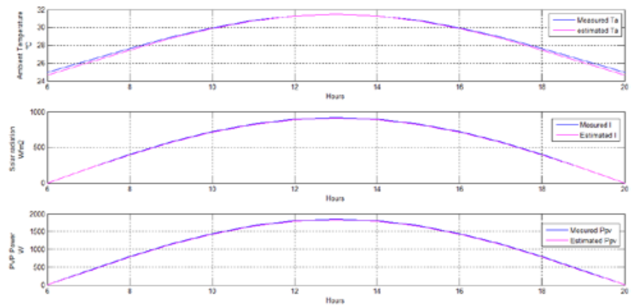


Fig. 6. Estimated and measured values of ambient temperature and solar radiation

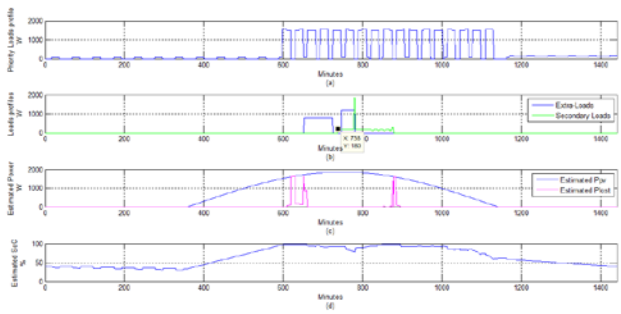


Fig.7. (a) Priority Loads profile, (b) Secondary Load and Extra_loads profiles, (c) Estimated produced power and Lost power, (d) Estimated SoC of one battery

5. Conclusion

Management PVPs/Batteries energy use for loads operation in an isolated chalet during summer season is proposed. The batteries charge state and PVP generated power are estimated using Kalman Filter and ANFIS technique. Then, a THPN formalism is used to model the system behavior. The proposed THPN methodology is applied to manage operation of loads in the chalet according to the available energy. Simulation results prove that the algorithm allows sufficient management of equipment operation.

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