State of Charge Rate for Photovoltaic Inverters with Adaptive Battery Storage

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Abstract

The paper presents a yearly optimal State of Charge (SoC) level calculating function to the grid connected residential size PV energy storage systems. Main aim is to decrease the electric grid peak load, energy need by offering an adaptive SoC value to the grid connected PV inverter with energy storage. The simulation utilizes a global optimization method with low computation need and it is tested on a yearlong measurement data which is unique in his segment.

The goal of the work is to lower the duration of the residential peak time and raise the off-peak time energy need by increasing the minimal SoC level of the grid connected PV inverter with energy storage without charging the energy storage in off-peak time. Meanwhile, the adaptive algorithm is minimizing the electric grid dependence, without adding as few as possible extra charge/discharge cycles to the energy storage.

In contrast of other widely known SoC algorithms the approach presented here has a verified capability to be used in all seasons. Moreover throughout this paper only real generating data of a small scale PV plant is used. Furthermore, corresponding formula is explored between the size of the energy storage, the saved energy and the PV production/energy need ratio in yearly base.

Keywords

Adaptive algorithm, grid connected PV system with energy storage, peak time demand shaving

1 Introduction

In Germany, the grid connected PV installation limit is approaching and in the near future only the energy storage systems, especially the decentralized systems could handle this problem. It is getting more and more important to utilize these grid connected systems (Figure 1.) to decrease the overall peak load on the electric grid, due to the fact that nowadays PV battery storage systems are not equipped with adaptive algorithm to manage peak load shaving, therefore, the stored energy is released without any kind of storage strategy until the minimal SoC is reached [1]. The cause behind this is to maximize the self PV energy usage, meaning that the energy should be used when it is produced. In such a case, it is beneficial to create a default "grid-friendly" algorithm which manages the State of Charge (SoC) level and the discharge period of the battery without utilizing off-peak charge/ peak discharge cycles, basically the discharge period is postponed when it really needed to accomplish the peak load shaving effect and to maximize the energy storage lifetime and the electric grid independent time.
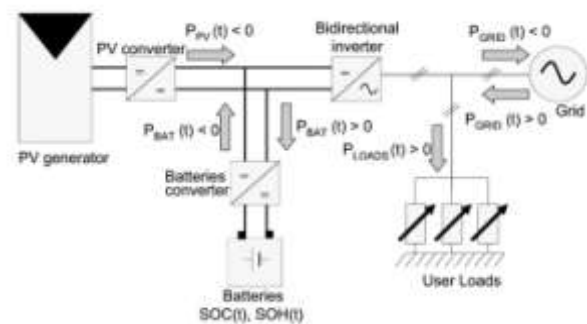

Fig. 1. Theoretical Power direction and sign convention in the system studied [1]

Keeping simplicity in mind, this algorithm was designed based on the PV power, load and time measurement of the energy storage's inverter. Additionally, global a optimization method was used which has relatively low computation need. The simulation was run on yearly database, which is unique capability in comparison with other discharge algorithms. To fine tune the algorithm parameters.

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D	Energy need in every 15 minutes	f_D	Derivate by demand
PV	PV energy production in every 15 minutes	f_{PV}	Derivate by PV energy production
D_c	Critical point energy need in every 15 minutes	f_{PVPV}	Double derivate by PV energy production
PV_C	Critical point PV energy production in every 15 minutes	f_{DD}	Double derivate by demand
f_{DPV}	Derivate by demand and by PV energy production	f_{PVD}	Derivate by PV energy production and by demand

2 Measurement data

It is well known that the corner stone of any simulation is the precise measurement data, therefore, the yearly energy production data of a 2kWp south oriented PV system located in Vác, Hungary, was collected to help to simulate real word conditions.

The PV system produced 2253 kWh in 2013. Although, the produced energy is just a few percent more than in Munich, Germany which is the cradle of the PV systems with energy storage [2].

On the other hand, an average 2800 kWh/year Hungarian household yearly energy need was used, which is based on measurement data. Because of the nature of the electric grid operation and the need to optimize the discharge cycle, the data resolution was set to 15 minutes which means that the household energy need and the energy production of the PV system was averaged by a moving average calculation in the resolution of 15 minutes. A more frequent time interval would have been unnecessary based on charging/discharging and conditioning characteristics of some energy storage systems, especially true for the AGM lead-acid batteries [3].
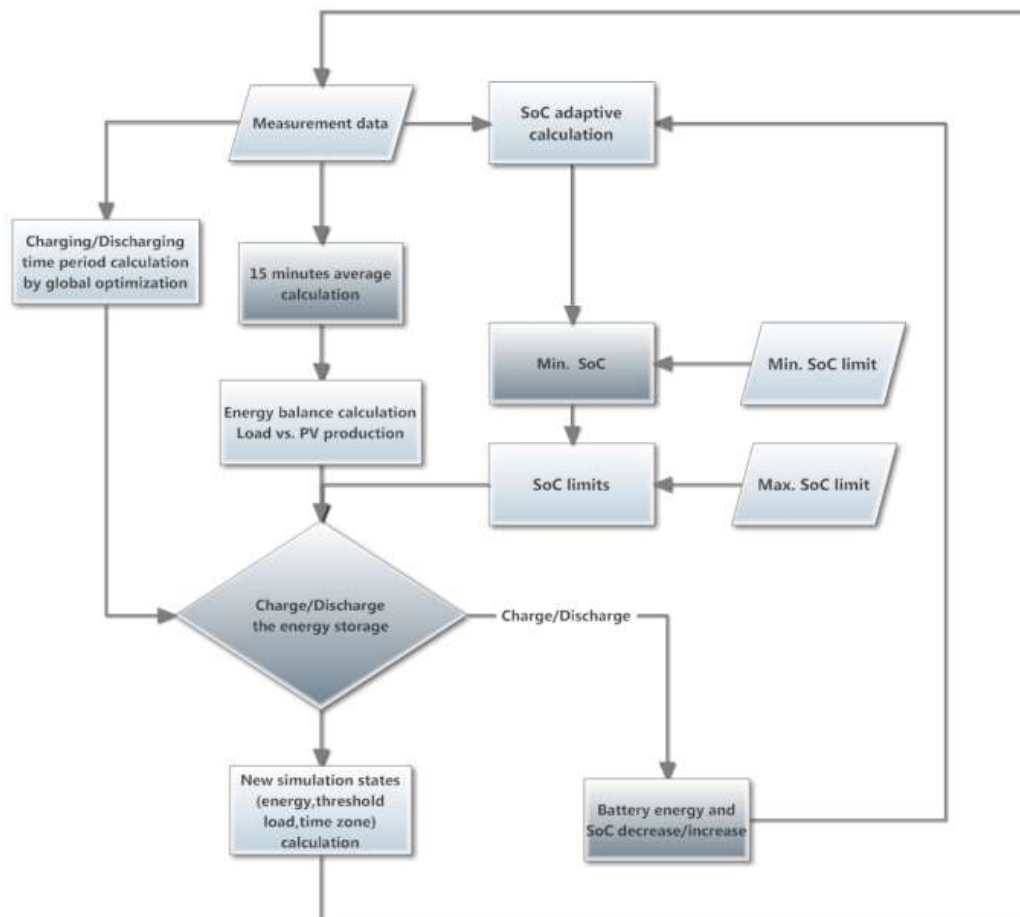
3. Structure of the simulation

Fig. 2. Flowchart of the proposed optimization methodology

On the 2nd Figure it shown that the simulation and the SoC calculating algorithm's behavior are mainly influenced by the previous 15 minutes battery storage inverter measurement data to determine the next 15 minutes inverter behavior. The following input parameters are given, or could be changed by the user;

- The upper and lower SoC limits of the energy storage
- The adaptive SoC range
- Turn on SoC limit of the threshold load

The following parameters are measured by the battery storage inverter;

- The date and the difference of the PV production and the household load
- SoC level of the energy storage
- Load

All of these parameters are used to decide that the PV energy should be stored or released, furthermore, it can be seen the simplicity was the corner stone of the adaptive algorithm.

The threshold load calculation method is based on the previous three day average night load (24:00-05:00). Furthermore, this function is easily feasible due to its simplicity.

The adaptive part of the simulation is realized by a plug-in algorithm built in the SoC limit calculating function, this algorithm has the role to fit adequate curve on the previous three day load and on the PV production data. Basically, the goal of the algorithm is to find their local maxima, using the mean of the previous three day local maxima (1). The next day SoC limit could be increased in peak PV production time period and decreased in the peak load period, if it possible. The global maximum is determined by the following equation (1);

$$f_D(D, PV)i + f_{PV}(D, PV)j - k \quad \text{(1)}$$
$$f_D(D, PV) = 0 \text{ and } f_{PV}(D, PV) = 0$$
$$D(D_c, PV_c) = f_{DD}(D_c, PV_c)f_{PVPV}(D_c, PV_c)$$
$$- [f_{DPV}(D_c, PV_c)]^2$$
$$If \ D > 0 \text{ and } f_{DD}(D_c, PV_c)$$
$$< 0 \text{ then } f(D, PV) \text{ has a relative maximum at } D_c, PV_c$$

As mentioned before, the goal of function (1) is to determine that the adoptive algorithm SoC level should be increased or decreased and to postpone the discharging of the stored PV energy for the peak load time period.

The algorithm has a built in threshold load "if" function which is turned on, if the SoC level drops to a certain value and it is set in default mode to 15% over the

minimal SoC value, basically the peak shaving effect is partly controlled by this function.

However, the overall charge/discharge period is not or minimally affected, due to the previous three day night load average calculation, which goal is to predict a lower threshold load, than the actual real load.

The adaptive algorithm is not intended to affect the overall yearly energy balance of the grid connected PV systems with energy storage; it only shifts the discharge period by increasing the SoC level minimal value. In case of the prediction of the next day PV production peak the global optimal algorithm method is justified based on the fixed PV module orientation, with this method the installed PV system resultant orientation can be determined. However, the peak load period for average household is strongly depends on the resident energy usage habit. Therefore, there are two options to set the discharge period.

The first is better in case of low PV energy storage system electric grid penetration, which is using the statistic peak load periods of the overall electric grid, based on experience and measurement data of the system operator.

The second option is better in case of high penetration which adjusts the energy storage discharge time period to the peak load period of the household. In case of the second option, the energy storage discharge period is adjusted by the peak load period.

The state of charge is calculated in every 15 minutes according to the energy flow from or into the energy storage and to the annual actual capacity of the energy storage. The maximum discharge power is set to a minimum of 10 hours discharge time period of the system. The annual capacity is based on the aging and self discharging properties of the energy storage, which in this case is an AGM lead-acid battery [4]. The battery charging strategies are not part of the article; therefore, it was not taken into consideration. The aging coefficient for 1000 cycle lifespan (at 30% Debt of Discharge) was calculated from the annual capacity to describe the capacity loss of the energy storage [4].

3 Initial conditions of the simulation

The default parameters (Table 1.) and the initial conditions of the simulation are set to represent a real word conditions.
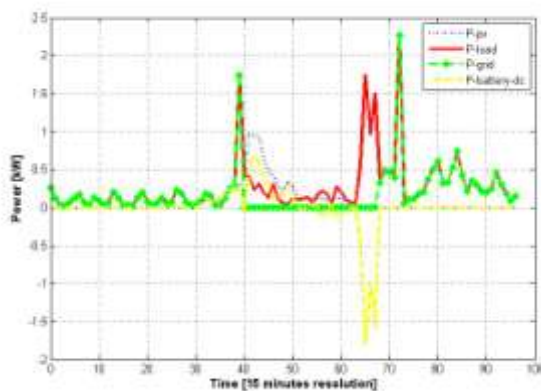
The following conditions were used in the simulation;

Table 1.   Simulation initial parameters

Name of parameters	Value	Unit
Inverter efficiency (DC/AC) [4]	95	%
AGM lead-acid energy storage capacity (12V)	1200	Ah
Energy storage ageing coefficient [5]	0,0012	1/h
Energy storage self discharging coefficient [5]	0,00014	1/h
Nominal charging/discharging time	10	h
Efficiency of the energy storage at charging/discharging [6]	90	%
Energy storage cut off min. SoC level	32	%
Energy storage cut off max. SoC level	90	%
Threshold load turn on SoC level	40	%
Threshold load (based on the last three day night load)	50	%
Adaptive algorithm SoC range	13	%

4 Power flow simulation results with fix parameters

The simulation was run on real yearlong PV production and household energy measurement data which summed up to 2253 kWh in case of a 2kWp PV system and the yearly energy need was set to 2800kWh which is average energy need of a Hungarian household.

Fig. 3. Simulation results without adoptive algorithm

On Fig. 3 it can be seen that the simulation results from 24th until 27th of January without the adoptive algorithm, in which the energy storage in discharged immediately without any kind of threshold load or discharge period timing.
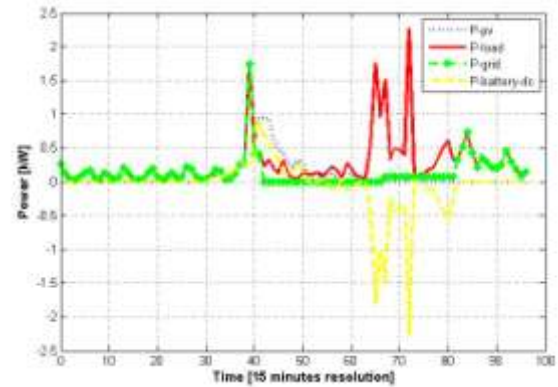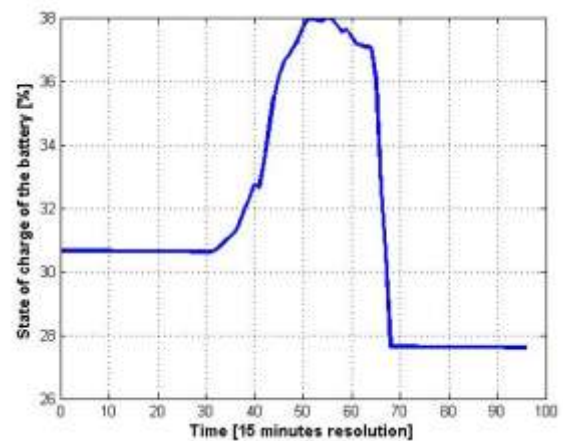

Fig. 4. Simulation results with adoptive algorithm

Fig. 4 shows the simulation results from 24th until 27th of January utilizing the adaptive algorithm which includes the threshold load switching function. As it can be seen in the Figure 4th, the peak load on the grid was significantly reduced even in winter time, when the daily PV energy

production is low.

Fig. 5. State of Charge level without adoptive algorithm

As illustrates, the SoC level of the energy storage is on Figure 5th and 6th and it could not increase as much as on 6th Figure due to the constant 30% minimal SoC limit.
The sharp increase of the minimal SoC level can be seen on the 7th Figure caused by the properly working adoptive algorithm. The SoC level is shown on 5th and on the 6th Figure from 24th until 27th of January, the connection between the minimal SoC level, which is influenced by the adaptive algorithm, and the real SoC level of the energy storage is well-marked.
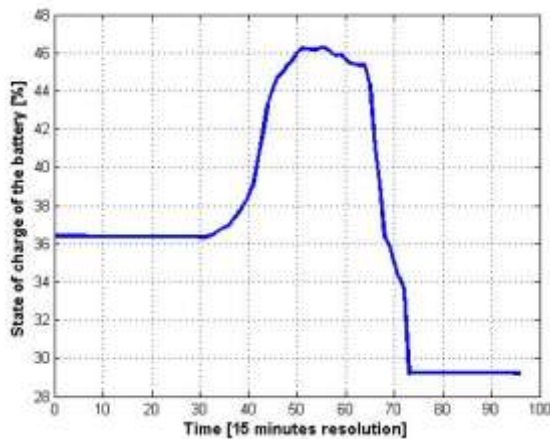
Fig. 6. State of Charge level with adoptive algorithm

As mentioned, real yearlong PV production and residential energy data was used which results that the calculated peak time period and the predetermined peak load (by grid operator) period by the adaptive algorithm is not the same, but really close to each other. According to the simulation, the calculated peak time period is shorter period of time, than the peak time period given by the grid operator. Without the algorithm the minimal SoC level would have been constant 30%, however, with the adaptive algorithm the increased the minimal SoC limit, which can be seen on the Figure 7th.
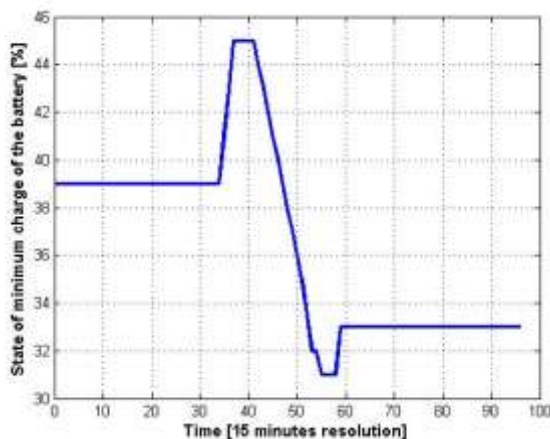

Fig. 7. Minimal State of Charge level with adoptive algorithm

The best way to measure the effectiveness of the adaptive SoC algorithm, which is basically a built in peak shaving algorithm, is to compare the peak time saved energy amount with and without the adaptive algorithm. Although, the yearly nominal energy comparison of the results would be delusive because in winter the electric

5 Simulation results with variable parameters

grid night peak load could be significantly higher than the peak load at noon and in winter time the daily PV energy output is 4-5 times lower than in summer in Hungary[2]. All of the mentioned facts result that there has to be a difference between saved energy amounts between the seasons. Therefore, two seasons were defined in the simulation; winter and summer. Winter represents the timeline from October until April and summer lasts from April until October. In both cases the peak time period was 7 hour long, lasting in winter from 7-9 am and from 5-8 pm, in summer it was shifted one hour forward to better fit to the electric grid summer load curve. According to the simulation it is resulted, only 6,5% stored energy increase using the adoptive algorithm, although the extra charge/discharge cycles were taken place in winter season when they were the most needed. Furthermore, the yearly saved energy amount was decreased only by 2,03% which is hopefully an acceptable loss for the customers for the greater good of the grid operator. Additionally, the winter peak time "saved" energy is usually the most expensive energy in the market [7].
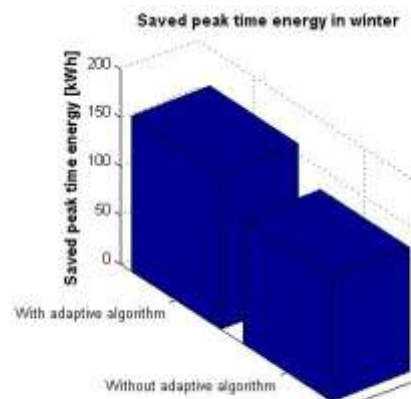

Fig. 8. Saved peak time energy from the grid in winter season with and without the adaptive algorithm (based on 2800kWh yearly energy need)

On Figure 8th it can be seen that the energy difference between the default and the adaptive discharging strategy is 31,97kWh in case of a 2800kWh yearly energy need residential customer equipped with a 2kWp PV system and 14,4kWh of AGM lead-acid battery storage which usable capacity is limited to 60% (from 30% to 90% SoC). It must be mentioned that the additional charging or discharging cycles resulted only 0,042% capacity loss to the energy storage and 87,4% of the extra energy storage capacity was used in winter season.
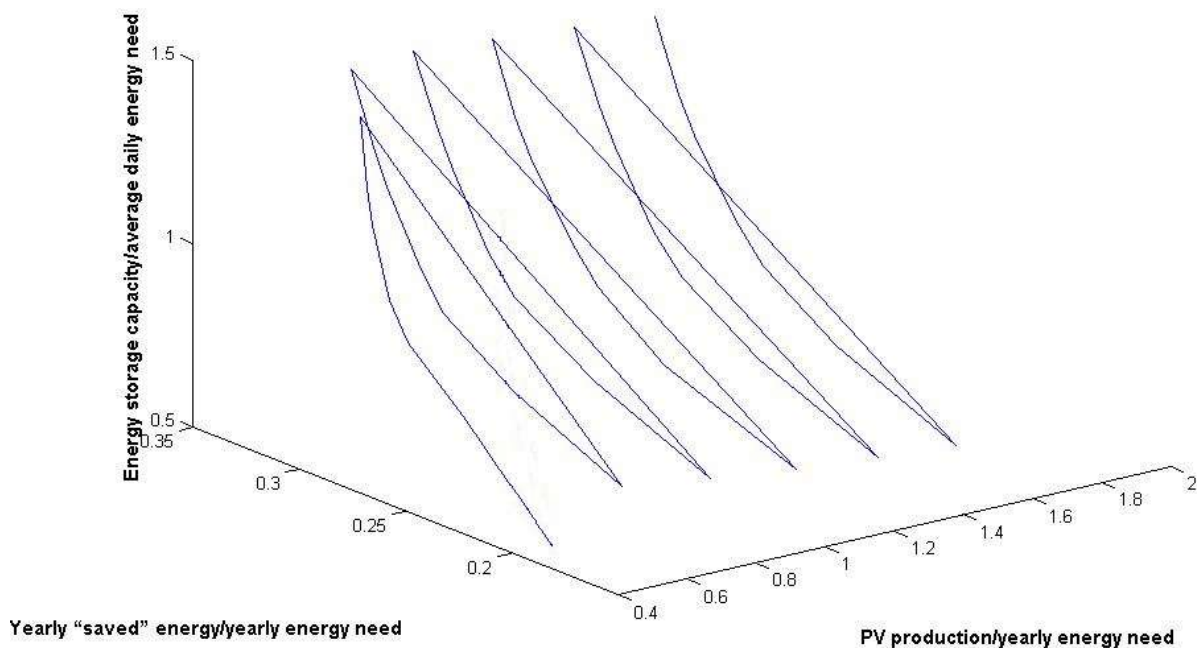
Fig. 9. Connection between the ratio of the usable energy storage capacity/average daily energy need, ratio of PV production/yearly energy need and the ratio of the yearly "saved" energy/yearly energy need

The primary goal of the simulation was create an adaptive algorithm which was shown in Chapter 4, but using the simulation results further correlation were able to be explored. To be exact, the equation between the size of the energy storage, the yearly energy production of the installed PV system and the saved energy from the gird of a given residential customer could be determined .

To create an equation between the mentioned parameters, relative input parameters were used which are the followings;

- Ratio of the yearly "saved" energy/yearly energy need
- Ratio of the PV production/yearly energy need
- Ratio of the usable the energy storage capacity/average daily energy need

The idea behind the variable parameter simulation is to find the transparency between the size of the energy storage, the yearlong energy need and the yearly energy production of the PV system. The equation, which fits to the corresponding data, is necessary to predict two of the missing parameters when one of them is known. Using a global optimization on the polynomial surface equation which is extracted from the simulation data, the missing parameters could be determined (Figure 9. and 10.). The

best way to demonstrate this capability is through an example; When there is a household with 1,2 ratio of PV production/yearly energy need, then the optimal size of the battery storage of the system is 14kWh system with the usable capacity of 8,4kWh.
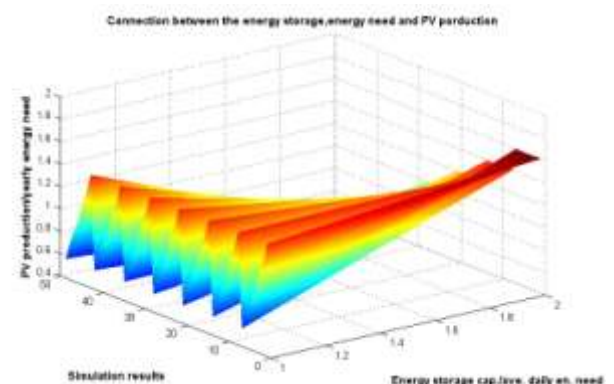

Fig. 10. Connection between the ratios of the usable energy storage capacity/average daily energy need and PV production/yearly energy need

6 Conclusion

According to the simulation results, the winter time peak load energy need was significantly reduced, to be exact, it was lowered with <u>31,97kWh, or 1,141%</u> of the yearly energy need in comparison with the "without adaptive algorithm" case. Furthermore, the saved energy was <u>decreased only by 0,254%</u> in comparison with the without adaptive algorithm case. However, the load curve was smoothened to help the grid operator, when it is really needed. As we all know, these kWh are the most worthy ones.

The adaptive algorithm worked well in summer season as well as in winter season achieving 87,4% of well. The peak energy/power was reduced, meanwhile only causing 0,042% greater capacity loss to the lead-acid battery storage in comparison with the default PV system energy storage discharging protocol.

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7 Biographies

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