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Energy-saving management modelling and optimization for lead-acid battery formation process

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Abstract. In this context, a typical lead-acid battery producing process is introduced. Based on the formation process, an efficiency management method is proposed. An optimization model with the objective to minimize the formation electricity cost in a single period is established. This optimization model considers several related constraints, together with two influencing factors including the transformation efficiency of IGBT charge-and-discharge machine and the time-of-use price. An example simulation is shown using PSO algorithm to solve this mathematic model, and the proposed optimization strategy is proved to be effective and learnable for energy-saving and efficiency optimization in battery producing industries.

1. Introduction

With the increasing challenges of energy and climate change, it is realistic and urgent to figure out how to manage power consumption loads in more optimal and better ways to make electrical power consumption more efficient.

As those industries developed vigorously, which have a great demand of batteries such as wind power, energy storage and electric vehicle industries, as a result, there has been a sharp rise in battery production amounts in recent years. The lead-acid battery has an extensive application in the fields of communication, railway transportation, power energy, aircraft industry and shipbuilding industries because of its prominent advantages: simple production process, cheap raw material, better power characteristic, low self-discharge rate and better high-and-low temperature performance. The lead-acid battery industry will still enjoy a great development and market potential in the next several decades [1].

As a high energy-consumption industry, the battery production gains more and more attention from the public about energy loss in battery production process [2,3]. The battery formation process, which is led by power to enable the internal chemical reaction of new produced batteries to proceed repeatedly and circularly in order to motivate the inside active substance, is one of the important steps in lead-acid battery manufacturing. The formation process takes up about 60-65% of the whole power consumption in battery production. For many researchers, it becomes an intensive problem to increase the utilization factor of power in formation process. An energy-saving manner to release the extra electric energy of the formation process to the power grid and utilize it again is put forward to solve this issue and has been applied abroad in actual production. However, releasing power directly from



lower voltage grid to higher voltage grid is specifically forbidden in China. A strategy is presented in [4], where energy discharged during the formation process is transmitted conversely to power grid by inverters in order to avoid being wasted on high-power resistors. Nevertheless, manufacturers may need to pay a lot for constructing appropriate power sub-networks to prevent the shock wave towards high voltage grid. As a result, the production cost cannot be reduced and the implementation will be difficult. Another method based on DC-bus topological structure has been come up with in [5] to decrease sub-networks construction cost by using the parallel high-capacity energy storage device as an energy buffer. This method will bring about extra production cost, as well as maintenance expense. A formation step control strategy is explained in [6] to optimize the massive batteries formation procedure and accomplish energy feedback without any pollution to the power grid. To be specific, the energy released in the charge process is directly utilized in the parallel discharge process.

In this paper, a comprehensive energy consumption optimization model considering charge and discharge machine (CDM) efficiency and time-of-use (TOU) price is established, aiming at reducing electricity cost and increasing energy utilization rate.

The paper is organized as following: a general introduction of lead-acid battery formation process is presented in Section 2, then an optimal model of battery formation process to realize minimum total electricity expense is established in Section 3. The optimal algorithm and a case study are shown in Section 4 and Section 5 respectively, and finally main conclusions are drawn in Section 6.

2. Analysis on lead-acid battery formation process

Nowadays, lead-acid batteries are among the most popular batteries, and their manufacturing is a typical high energy-consumption industry. The raw material of lead-acid battery includes lead ingot, lead powder, vitriol, battery lead plate, battery holder and other active substance and so on [7]. The electricity expense occupies about 90% of the overall energy cost of the enterprise, therefore there is an enormous energy-saving potential in the electricity consumption process.

2.1. The lead-acid battery formation process

The formation process is indispensable in the lead-acid battery production before finished products leaving the factory. The difference among batteries in series connection can be reduced by optimizing their formation process and using advanced electric facilities. Through these ways the quality of batteries can be improved including service life and initial capacity.

Basically, the formation process is to enable the internal reaction of new batteries by charging and discharging circularly in order to motivate the active substance such as PbO_2 and spongy lead so that the finished battery is capable of storing and generating electric power [8]. The battery formation process varies among different types of batteries and different manufacturers. Anyway, batteries always charge with constant current or constant voltage, and discharge in a constant-current way. The only difference in formation process of batteries with various types and capacities is the charge-and-discharge time.

2.2. The CDM for formation process

An energy saving formation process is dependent on an ideal CDM. The CDMs for lead-acid battery can be regarded as a power source that supplies batteries with constant-current electricity and a power consumption load as well that transfers energy back to power grid to achieve energy regeneration. In consideration of the current situation that the equipment is not advanced enough and energy consumption is huge in most battery manufacture factories, it is imperative to upgrade electrical facilities and update the manufacture techniques to save energy and reduce emission. It is more efficient in formation process and satisfies the demand for future development of battery producing industries to adapt Insulated Gate Bipolar Transistor (IGBT) charge and discharge device than Silicon Controlled Rectifier (SCR).

The electricity transformation efficiency is the most important factor for IGBT CDM in battery producing process. In the formation process, transformation efficiency has a direct relationship with

electric power consumption. If the transformation efficiency is not perfect, the economy cost will be increased accordingly. As a result, a high level transformation efficiency is a key-point for energy saving.

$$\eta = \frac{P_k}{P_s} \times 100\% \tag{1}$$

where, η means the transformation efficiency of CDM, P_k and P_s mean the output power and input power of CDM respectively. This transformation efficiency of IGBT is relevant to its load rate and temperature. The relationship is pictured in figure 1.

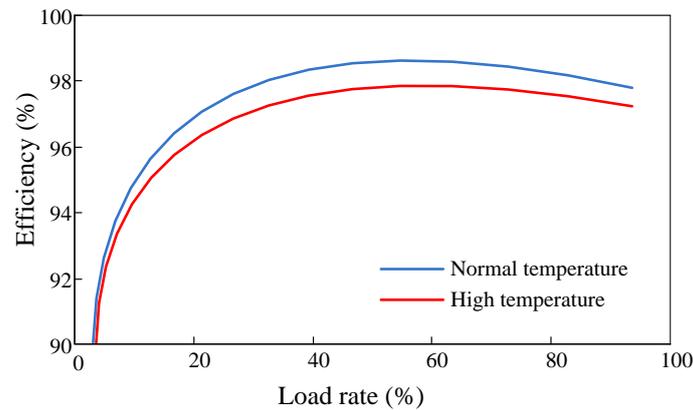


Figure 1. Power efficiency curve of IGBT CDM.

The load rate β of IGBT is

$$\beta = \frac{P}{P_0} \times 100\% \tag{2}$$

where, P and P_0 mean the load power and rated power of CDM.

Figure 1 indicates that the transformation efficiency η trend is not constant with the load rate β . There is a sharp increase in transformation efficiency within the section where the load rate ranges from 0 to 30%. While the load rate grows from 30% to 100%, transformation efficiency keeps at a high level and even goes a little lower near the end. Moreover, ignoring other factors, the increase of operating temperature will make transformation efficiency drop.

3. Construction of optimal model on formation process

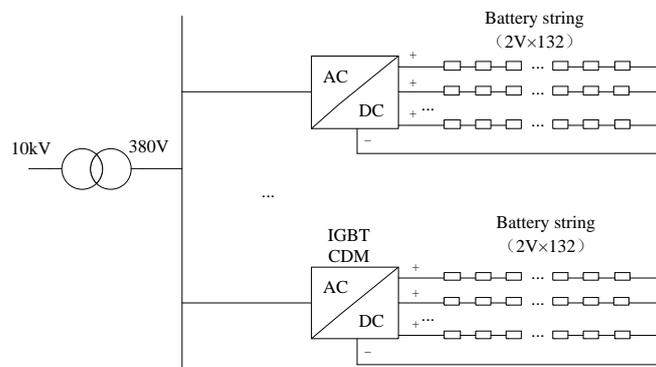


Figure 2. Formation progress topology.

The main equipment of formation process is CDM. Each machine carries more than one string of batteries. Supposing that the charging voltage is 400 V, meaning that every string has 132 batteries and the finished product is 2V-battery. Obviously every battery in the string can get a voltage about 3 V. The concrete structure of formation is shown in figure 2.

3.1. Assumptions

To simplify the model, we make following assumptions:

- Every CDM can start or stop at any time, with no time limit and no times limit. Overlooking the temperature increase and the service life reduce caused by the start-stop, we just take the start-stop loss into consideration when every start-stop occurs.
- Regard every string of batteries as one target, and ignore their internal difference [9]. Never would a battery break down when formation proceed.
- Do not consider electricity quality.
- Every string of batteries has the same formation period, while their formation power curve may be different.
- Overlook the time of replacing new batteries. The target time section is any complete period of formation.
- The efficiency of IGBT CDM is influenced by temperature and load rate, but in this paper only the load rate is considered.

3.2. The objective function

Because the formation curves of every string are different, batteries in different strings can hardly charge at the same time. Either all strings charging or standing is low efficient. To avoid this, we take several actions:

- According to TOU electricity price, we change the formation start moment of every string in order that more batteries can charge during bottom load periods and keep standing or discharge during peak load periods.
- Optimize the formation start moment of every string to avoid all strings batteries discharging at the same time.
- Since high load rate makes high transformation efficiency, we artificially change the string numbers connected to every IGBT machine to keep the load rate at a high level.

In the paper, the formation period T is the targeted time section. An optimal model is established to minimize the electricity cost of formation process

$$C = \min_{u_j(t)} \left\{ \rho(t) \sum_{t=1}^T \sum_{j=1}^J \left(\frac{u_j(t) P_j(t)}{\eta(P_j(t))} + C_j(t) \right) \right\} \quad (3)$$

where, every interval is numbered by t , $t=1, \dots, T$, and $\rho(t)$ means TOU electricity price. For each CDM indexed by j , $P_j(t)$ means the load power, $C_j(t)$ means the start-stop loss and $u_j(t)$ means a state variable which equals 1 when machine works and equals 0 when machine stops. Here the load power of CDM j is

$$P_j(t) = \sum_{k_i(t)=j} P_i(t), \quad k_i(t) = \{1, \dots, J\} \quad (4)$$

where, i means the index of string of batteries ($i=1, 2, \dots, I$). $k_i(t)$ means the number of CDM that the i^{th} string connected to in t^{th} interval. $P_i(t)$ means power of the i^{th} string of batteries.

The charging power of each string is related to the formation power and formation start moment.

$$P_i(t) = f_i(t - t_{0i}) \quad (5)$$

where, for the i^{th} string, $f_i(t)$ means the formation power curve function, and t_{0i} means the formation start moment.

We overlook the time for replacing new battery string, hence the power curve of every string is a periodic function with a period T .

$$f_i(t+T) = f_i(t) \quad (6)$$

where, the period T is determined by a given battery power curve. In this context, the formation period of each string of batteries is the same, although their power curves may be different.

Every CDM will bring about some energy loss when a start or a stop occurs. The start-stop loss is defined as:

$$C_j(t) = [1 - u_j(t-1)] \cdot u_j(t) \cdot C_s + u_j(t-1) \cdot [1 - u(t)] \cdot C_t \quad (7)$$

where, C_s means the start loss and C_t means stop loss. Assume that $C_s = C_t$.

3.3. The constraint conditions

- Load rate constraint

$$\alpha P_{j0} \leq P_j(t) \leq P_{j0}, \quad \forall t \geq 0 \quad (8)$$

where, $0 \leq \alpha \leq 1$. To keep the CDM within a high efficiency range, we set $\alpha \geq 0.3$.

- Overall power constraint

$$\sum_{i=1}^I f(t - t_{0i}) = \sum_{j=1}^J u_j(t) P_j(t) > 0, \quad \forall t \geq 0 \quad (9)$$

which indicates that the overall power is positive at any moment in the dispatch period T .

- Formation start moment constraint

$$0 \leq t_{0i} \leq T \quad (10)$$

which shows that the formation start moment of each string must be within the dispatch period T .

- Switch intervals constraint

$$|t_{i1} - t_{i2}| \geq t_{is}, \quad \forall t_{i1} \neq t_{i2} \in A, \quad A = \{t_i | k_i(t) - k_i(t-1) \neq 0\}, \quad t = 2, \dots, T \quad (11)$$

where, A means the set of switch intervals and t_{is} means the minimum switch interval time.

- Total switch times constraint

$$\sum_{t=1}^T m_{i,t} \leq n_i \quad (12)$$

where, $m_{i,t}$ represents whether the i^{th} string of batteries switches within time section t . $m_{i,t} = 1$ if $k_i(t) - k_i(t-1) \neq 0$. n_i means the maximum switch times for each string within the dispatch period T .

4. Algorithm for model solving

The model is solved by Particle Swarm Optimization (PSO) algorithm. In the optimization model, $k_i(t)$ and t_{0i} mean optimized variables, and the fitness function is the objective function C . To simplify the computing process, we use special battery strings allocation method to optimize $k_i(t)$:

- Firstly, sort all strings of batteries at every time interval according to their power value;
- Then, combine the biggest two strings and the smallest two strings as a pair, and the rest pairs can be combined in the same way;

- At last, connect the string pairs to every CDM.

The advantage of this method is that every CDM has similar load power and accordingly power releasing will hardly occur.

The PSO is applied like that: firstly, we pre-set a random number for t_{0i} , and figure out $k_i(t)$. Then let computer judge whether the combination $(t_{0i}, k_i(t))$ satisfies the given constraints. If not, pre-set a number for t_{0i} again until the combination meet all constraints. These combinations are particle swarm. The most optimal particle will be picked out from the swarm to be applied into the optimization algorithm through a number of iterations. Finally, we can get the optimum solution that makes the overall formation operation cost minimum.

The value of key parameters are given as follows: the particle swarm size $M=100$, the inertia factor (the velocity of every particle) $w=0.6$, learning factor $c_1 = c_2 = 2$, convergence index $\varepsilon=0.0005$.

The formation period of batteries is divided into T intervals as the dispatch period. If let the minimum switch interval equal dispatch period, then two constraints can be removed: (1) the switch intervals constraint; (2) the switch time constraint.

5. Case study

5.1. The parameters of case

The management model and strategy for formation process in a certain lead-acid battery enterprise is taken as an example. Main products in this enterprise are 2 V batteries, which are charged by IGBT CDM in a constant-current formation mode. The charging voltage is about 400 V and there are 132 batteries in every string. The whole formation process lasts more than 100 hours while the charging, discharging, standing processes are conducted alternately. Also, the formation current and voltage are precisely set in order to ensure the quality of batteries.

Two kinds of 2 V batteries are taken as examples which have different capacity (400 Ah and 500 Ah) and the same formation period. Based on the practical operation data, the information of formation process (voltage, current, duration, etc.) are neatened in tables 1 and 2.

Table 1. Formation information of 2 V battery with capacity of 400 Ah.

Steps	Formation process	Current (A)	Time interval (h)	Voltage (V)
1	Charging	16	4	210~215
2	Charging	48	40	215~265
3	Charging	20	8	265~268
4	Standing	0	1	-
5	Discharging	40	8	204~197
6	Charging	48	8	206~272
7	Charging	24	36	272~275
8	Standing	0	1	-
9	Discharging	40	10	207~191
10	Discharging	48	11	216~260
11	Charging	20	4	260~271
12	Charging	4	4	271

The company is equipped with two kinds IGBT CDMs. This study takes one of the two IGBT CDMs with a capacity of 60 kW into consideration. Based on the operation manual, the data pertaining to the relationship between the transmission efficiency and load rate of IGBT CDM is presented in table 3, according to which the transmission efficiency function curve can be fitted. We can also get the transmission efficiency value of every load rate from the fitting function curve in figure 1.

Table 2. Formation information of 2 V battery with capacity 500 Ah.

Steps	Formation process	Current (A)	Time interval (h)	Voltage (V)
1	Charging	20	4	211
2	Charging	50	45	221~268
3	Charging	25	8	253~264
4	Standing	0	1	-
5	Discharging	50	8	202~205
6	Charging	50	10	206~273
7	Charging	30	32	273~274
8	Standing	0	1	-
9	Discharging	50	8	207~191
10	Charging	50	12	216~260
11	Charging	25	4	271
12	Charging	5	2	271

Table 3. Transformation parameter of 60 kW rated capacity IGBT CDM in 23 centigrade.

Load rate (%)	Efficiency (%)
5	94.80
10	97.04
15	97.66
20	98.01
25	98.18
30	98.32
50	98.61
75	98.63
100	98.58

The parameters in the model are as follows:

- The start-stop loss is set to be 0.5 kW, that is to say $C_j(t)=0.5$.
- 5 CDMs work in parallel and 18 strings of batteries are connected to these CDMs.
- The capacity of every CDM is 60 kW.
- Assuming that the first 8 strings of batteries follow the first kind battery formation model while the rest 10 strings follow the second kind.
- 4 strings of batteries can be connected to every CDM at most.
- TOU price: peak load time lasts for 16 hours with a price of 1.2 RMB/kWh while bottom load time lasts for 8 hours with a price of 0.56 RMB/kWh.
- Punishing price is set to be 3 RMB/kWh.
- The formation period $T=135$ hours is divided into 135 dispatch intervals.

5.2. Interpretation for the result of optimization model

According to the steps presented above, we can solve the formation management optimization model. For comparison, two optimizations are carried out: in optimization I, only t_{0i} is optimized while $k_i(t)$ remains unchanged; in optimization II, two optimized variables both t_{0i} and $k_i(t)$ are all taken into consideration. That is to say, we optimize not only the start moment of every battery string but also the battery strings allocation method. The power curve before optimization is shown in figure 3, and the optimal formation power curves are shown in figures 4 and 5.

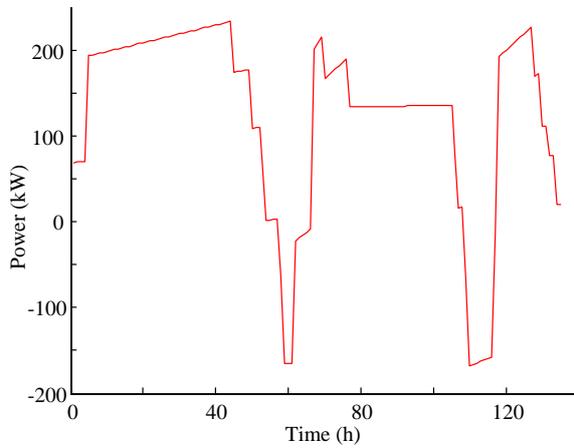


Figure 3. Power curve before optimization.

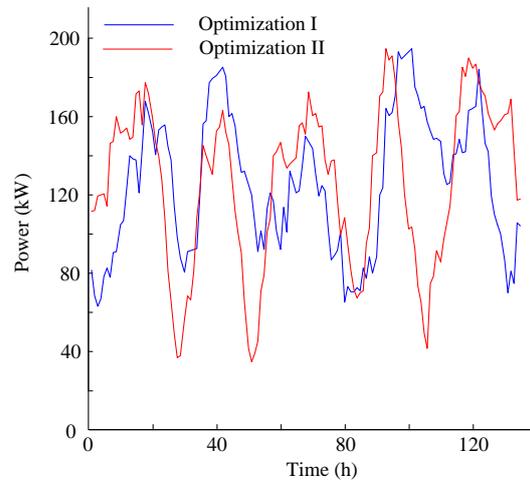


Figure 4. Power curve of optimization I and II.

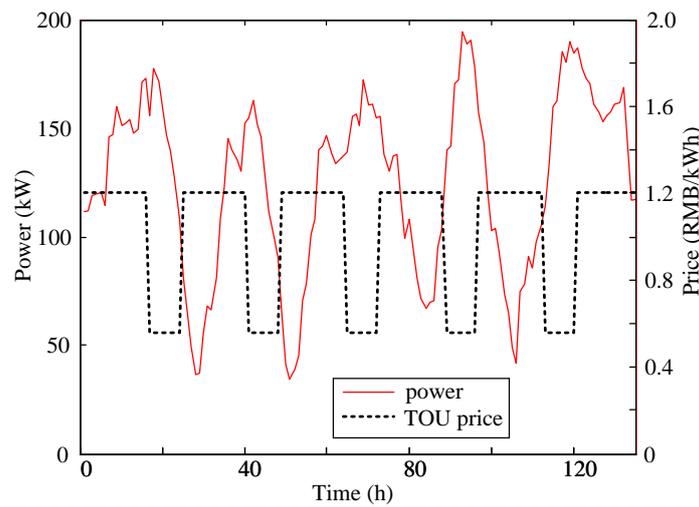


Figure 5. Power curve of optimization II and TOU price.

Table 4. Results comparison before and after optimization.

Results comparison	Before optimization	Optimization I	Optimization II
Formation operation cost (RMB)	27994.03	18887.31	18617.10
Maximum power (kW)	233.09	194.71	194.22
Minimum power (kW)	-168.03	62.99	34.35
The peak valley power difference (kW)	401.12	131.72	159.87
Average efficiency of CDMs	87.17%	87.96%	87.96%
Maximum time of power releasing (h)	18	0	0

As table 4 indicates, the electricity costs after optimization I and II are reduced, meaning that the batteries producing cost is decreased. Similarly, we find that power releasing caused by formation discharging does not occur after optimization any more. That is because we changed the start moment of formation process and used a special batteries strings allocation optimization method. The peak valley power difference before and after the optimization also decreases. From figure 4, we infer that

the overall formation power distribution is skewing to the bottom load time section. The characteristic of overall power consumption presents to be higher when electricity price is low while lower when within peak electricity price, which is in accordance with the purpose of the objective function.

However, comparing optimization I with II, the difference between peak and bottom power value is widen from 131.72 kW to 159.87 kW when the battery allocation method is adapted. That is because the more optimal battery allocation is, the more influential the TOU electricity price is by inducing power consumers move load to lower-price time sections in order to save their electricity costs. Therefore, a new load peak will appear and is likely to bring about power crash. This is the feature of this proposed optimization strategy: for the sake of lead-acid batteries manufacturers, it does not make any constraints upon the difference between peak and valley value of power curve.

6. Conclusions

In this paper, a comprehensive formation process optimization model considering transformation efficiency of CDMs and TOU price was built to reduce the overall formation electricity costs. Based on the TOU price, the formation start moment was optimized to make heavy current in bottom price time while slight current or standing in peak price time sections. Meanwhile, based on the CDM transformation efficiency curve, a reasonable allocation method for battery strings connected to CDMs was applied in order to avoid lower efficiency for CDMs caused by slight load rate. In a more general situation, the proposed optimization model will be of great benefit to the lead-acid battery manufacturer to decrease the total cost.

Acknowledgments

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