Optimal Operation Strategy of Energy Storage System in PV-integrated EV Charging Station Based on improved NSGA-II

Shanshan Shi¹, Yu Zhang¹, Zhangjie Fu², Qin Xu¹, Qixing Yang⁴*, Chen Fang¹, and Shuntian Shi³

¹Electric Power Research Institute, State Grid Shanghai Municipal Electric Power Company, Shanghai, 200437, China
²Shanghai University of Electric Power, Shanghai, 200090, China
³EPTC(BEIJING) Electric Power Research Institute, Beijing, 100000, China
*Corresponding author’s e-mail: wangyufei@shiep.edu.cn

Abstract. In order to realize the economic operation of PV-integrated EV charging station and reduce the additional construction and transformation brought by the charging station to the power grid, an optimal operation strategy of energy storage system in PV-integrated EV charging station based on the improved NSGA-II is proposed. Firstly, with the power of the energy storage system and the capacity of the transformer as constraints, the optimization operation model of energy storage is built with the minimum variance of side loads of the power grid and the minimum purchase cost from the power grid as objective functions. Then, aiming at the low efficiency of the traditional NSGA-II gene recombination operator, the improved NSGA-II based on the adaptive recombination operator is proposed to solve the model, and the optimal operation strategy is obtained from the final Pareto solution set by using fuzzy clustering method. Finally, the effectiveness of the proposed algorithm is verified by example simulation, indicating that the improved NSGA-II can further improve the operation economy of charging stations and the load level of the power grid.

1. Introduction
The rapid spread of electric vehicles (EVs) has made people increasingly concerned about public charging facilities[1]. PV-integrated EV charging station as a new charging facility, can be realized on the integration of renewable energy and EVs, has been widely recognized[2]. As an important part of PV-integrated EV charging station, the energy storage system has certain controllable net power. On the one hand, reasonable storage system operation strategy can promote the in situ of PV power given, at the same time to reduce the charging station dependence on network power demand side[3]. On the other hand, the fluctuation of EV load can be stabilized to reduce the impact on power grid[4]. Therefore, the research on optimal operation of energy storage system in charging station is of great significance.

At present, the research on optimal operation of energy storage system at home and abroad has achieved relevant results. In the literature[5], hybrid integer linear programming is adopted to solve the scheduling model of hybrid energy storage system with multiple time scales, providing a reasonable scheduling scheme for energy storage for operators. In the literature[6-7], a model for energy storage optimization operation is established based on the system operation cost and battery cycle quantity as the objective function. A solution is obtained by using the Nondominated Sorting
Genetic Algorithm II (NSGA-II) to improve the overall performance of the system. In literature[8], genetic algorithm (GA) is adopted to solve the optimal operation model of energy storage taking into account user demand response, and critical conditions are combined to verify that the energy storage system can effectively improve the operation level of distribution network. In literature[9], the quadratic programming mathematical model is adopted to optimize the charge-discharge power of energy storage. At the same time, GA is combined to obtain the optimal operation strategy suitable for energy storage power station.

The intelligent algorithms involved in the optimization operation of the energy storage system mentioned above include hybrid integer linear programming, GA and NSGA-II. The hybrid integer linear programming has the advantage that the solution of clear, simple and quick, but for solving the objective function and constraint conditions for the nonlinear characteristics of the model is difficult[10]. GA and NSGA-II according to the characteristics of the energy storage multidimensional nonlinear optimal operation has good applicability and solved with the domination relationship of the two objective optimization problem. But with the increase of the number and the problem of dimension optimization goal, the shortcomings of traditional NSGA-II, such as slow convergence speed and low search accuracy[11], will affect the final strategy of optimal operation of the energy storage system.

In view of this, from the overall perspective of the PV-integrated EV charging station, the paper analyzes the operation economy of the charging station and the fluctuation level of the load on the side of the network, and establishes the energy storage optimization operation model aiming at the minimum variance of the load on the side of the power grid and the minimum purchase cost from the power grid. Thus, the improved NSGA-II is proposed to solve the model, and under the MATLAB simulation environment, the influence of improved NSGA-II and traditional NSGA-II corresponding energy storage optimization operation strategy on the grid side load fluctuation level and the operation economy of charging station is analyzed to verify the feasibility and effectiveness of the proposed optimization algorithm.

2. The operating model of energy storage system in PV-integrated EV charging station
The optimal operation of the energy storage system should take into account both the economic index of the charging station and the technical index of the grid side operation. On the basis of satisfying the load demand in the station, the minimum purchase cost and the minimum variance of the side load are selected as the optimization objectives. The optimization goal is to minimize the purchase cost of power from the grid, which can reduce the unnecessary operating cost of charging stations. Taking the minimum variance of grid side load as the optimization goal can effectively reduce the fluctuation of power supply at the grid side, make the equivalent load curve at the grid side tend to be flat, and ensure the smooth operation of the grid.

2.1. Objective function

2.1.1. Minimize grid side load variance

The variance of grid side load can reflect the fluctuation level of grid side load. The smaller the value is, the more stable the load fluctuation will be. Taking the power supply power of each time period of the power grid as the control variable, the minimum variance model of side load of the power grid is established, as shown in equation (1):

$$f_i = \min \frac{1}{T} \sum_{t=1}^{T} (P_{grid}(t) - P_{grid\_ave})^2$$

(1)

Where, $P_{grid}(t)$ is the power supply of the grid in time period $t$; $T$ is the number of time periods. In this paper, it is considered that the operation cycle is one day, and 1h is taken as the unit time period, that is, $T=24$. $P_{grid\_ave}$ is the average power supplied by the grid during the operating cycle, namely,
2.1.2. Minimum purchase cost from the grid

Based on the time-of-use electricity price, the energy storage system and the power grid coordinate to supply power to the load, which can reduce the power demand of the charging station to the power grid, and establish the minimum power purchase cost model from the power grid, as shown in equation (3):

\[
f_2 = \min \sum_{t=1}^{T} P_{grid}(t) \times P_{rice}(t) \Delta t
\]

Where, \(P_{rice}(t)\) is the power grid price at time period \(t\); take 1h as the unit time period, namely, \(\Delta t = 1\).

2.2. Constraint conditions

2.2.1. Energy storage system operation constraint

\[-P_{Bess,N} \leq P_{Bess}(t) \leq P_{Bess,N}\]

Where, \(P_{Bess}(t)\) is the charging and discharging power of the energy storage system at time period \(t\) (charging is positive, discharging is negative); \(P_{Bess,N}\) is the rated power of the energy storage system.

2.2.2. Energy storage system SOC constraint

Excessive charging and discharging of the energy storage system will affect its service life. The SOC of the energy storage system shall meet the following constraints:

\[SOC_{\min} \leq SOC(t) \leq SOC_{\max}\]

Where, \(SOC(t)\) is the charged state of the energy storage system in time period \(t\); \(SOC_{\max}\) and \(SOC_{\min}\) are the upper and lower limits of the charged state respectively.

The \(SOC\) value at time \(t\) is related to the \(SOC\) value at time \(t-1\) and the charging and discharging power of the energy storage system at this period, which can be expressed as:

\[SOC(t) = SOC(t-1) + \frac{P_{Bess}(t)\Delta t}{E_{Bess,N}}\]

Where, \(E_{Bess,N}\) is the rated capacity of the energy storage system.

2.2.3. System power balance constraint

The charging power of EVs, PV power generation, charging and discharging power of energy storage system and power supply power of power grid should be kept in balance, namely,

\[P_{PV}(t) + P_{grid}(t) = P_{load}(t) + P_{Bess}(t)\]

Where, \(P_{PV}(t)\) is the PV power of time period \(t\); \(P_{load}(t)\) is the load charging power of time period \(t\).

2.2.4. Grid power supply constraint

The upper limit of power supply of the power network is limited by the rated capacity of PV-integrated EV charging station transformer and AC/DC converter module, as shown below:

\[P_{grid} \leq \min(P_{T1}, P_{AD})\]
Where, $P_{Tr}$ and $P_{AD}$ are rated capacity of charging station transformer and AC/DC converter module respectively.

3. Optimization operation strategy of energy storage based on improved NSGA-II

3.1. Defects of traditional NSGA-II
NSGA-II is an intelligent algorithm for multi-objective optimization problems. NSGA-II used random method to generate parent population, then through the Simulated Binary Crossover (SBX) and Polynomial Mutation (PM) combined with genetic recombination operators to produce offspring, but in solving multi-objective optimization problem of unable to predict in advance the effectiveness of a single gene recombination operator to solve the problem above, may result in slow speed of search, optimization and low precision.

In this paper, the improved NSGA-II based on adaptive gene recombination operator is proposed to solve the optimization problem of energy storage system operation.

3.2. Improved NSGA-II
In view of the defects of traditional NSGA-II gene recombination operators, in order to improve the global search speed and optimization accuracy of the algorithm, gene recombination operators can be divided into two categories according to the spatial distribution characteristics of the offspring generated by gene recombination operators[12]: 1) Gene recombination operators whose offspring are distributed along the axis centered on the parent; 2) The gene recombination operator of the progeny spreading around with the parent as the center.

In order to give full play to the advantages of the above two types of recombination operators, SBX and PM combination, Order Crossover (OX) combines with PM, Parent-Centric Crossover (PCX) combines with PM, and Simplex Crossover (SPX) combines with PM are introduced for crossover mutation of algorithms. Among them, the offspring produced based on SBX and OX were distributed along the axis with the parent as the center[13], while the offspring produced based on PCX and SPX were distributed in all directions with the parent as the center[14-15], which of the above two kinds of genetic recombination operator search mechanism is complementary, can increase the genetic diversity of population, raise the global search speed and efficiency of the algorithm.

In the optimization iteration process of the algorithm, in order to give full play to the advantages of each recombination operator in different periods, a feedback loop of gene recombination operator selection is established, as shown in figure 1.

![Feedback loop of recombination operators.](image)

Figure 1. Feedback loop of recombination operators.

It can be seen from figure 1 that in each iteration of the algorithm, only one gene recombination operator is selected to perform cross mutation, and the probability of each gene recombination operator being selected is defined as $\{Y_1, Y_2, \ldots, Y_L\}$, $Y_i \in (0,1)$, where $L$ is the number of gene
recombination operators. In the initialization stage, $Y_i = 1/L$. At the end of each iteration, the selection probability of each gene recombination operator will be updated periodically, namely,

$$Y_i = \frac{C_i + \tau}{\sum_{i=1}^{L} (C_i + \tau)}$$  \hspace{1cm} (9)$$

Where, $C_i$ is the number of successful offspring produced by gene recombination operator $i$ (individuals in non-dominant layer $F_1$); $\tau$ is a constant factor, in order to avoid the accidental loss of gene recombination operator in the iterative process of the algorithm, it is defined $\tau = 1$.

Through the above improved NSGA-II solution based on adaptive gene recombination operator, a set of Pareto optimal solutions is obtained, which can provide a variety of solutions for optimal operation of the energy storage system. Therefore, fuzzy clustering method[16] is adopted to select the optimal operation strategy of the energy storage system.

3.3. The solution process of energy storage system optimization operation strategy

The process of solving the optimal operation strategy of energy storage system in PV-integrated EV charging station based on the improved NSGA-II algorithm is shown in figure 2. In the initialization stage, the charging station obtains basic information, including day-ahead PV power forecast data, typical daily load data and time-of-use electricity price data, etc, and then makes the optimal operation strategy of the energy storage system according to the steps shown in figure 2.

![Figure 2. The flowchart of energy storage operation strategy.](image-url)
4. Analysis of examples

In order to verify the effectiveness of the proposed improved NSGA-II for solving the optimization operation strategy of the energy storage system in PV-integrated EV charging station, the simulation analysis is carried out under the PV-integrated EV charging station architecture as shown in figure 3.

In the PV-integrated EV charging station, the principle of PV power giving priority to load power supply is followed, so as to reduce the demand of charging station on power grid. When PV power is higher than the load charging power, the remaining PV power can be used to charge the energy storage battery pack with the power not enough. When PV power is less than the charging power of load, and the time-of-use price is valley price, the public grid will charge the energy storage battery packs with less power and supply power to the balance load at the same time. When the PV power is less than the load charging power, and the time-of-use price is higher than the valley price, the energy storage battery pack meeting the discharge condition and the public grid coordinate and cooperate to supply power to the differential load.

4.1. The data of examples

In order to analyze and solve the problem of optimal operation of the energy storage system in PV-integrated EV charging station, the following conditions are set.

- The PV-integrated EV charging station adopts DC rapid charging mode. The number of charging piles in the station is thirty, and the charging power of a single charging pile is 60kW. The rated power of the lithium battery energy storage system is 2MW, the rated power is 10MWh and the rated capacity of the distribution transformer is 2MVA. Rated power of AC/DC converter module is 1500kW.

- Assume that the number of electric cars within the service range of the charging station is five hundred, including electric private cars and electric taxis, with a ratio of 7:3. According to the experimental statistics of NHTS[17], the initial charging time of electric private cars follows the normal distribution of N(17.6,3.4), and the daily driving distance follows the Log-N(45,0.88) log-normal distribution. Assuming that the initial charging time of electric taxis is uniformly distributed and the daily driving distance is normally distributed in N(155.02,41.53). Calculate and analyze the amount of charging of EVs in stations at different times of day, and get the daily charging load demand through Monte Carlo algorithm. The power curve is shown in figure 4.
Based on the predicted PV power data of typical days, the PV output ratio is set to be 18%, and the power curve is shown in figure 5.

The electricity purchase price of the PV-integrated EV charging station to the power grid adopts the electricity sale price of the Shanghai power grid[18].

In the optimized scenario of PV-integrated EV charging station, the parameters of traditional NSGA-II and improved NSGA-II were set as follows: initial population N is 100, evolutionary algebra is 500 generations, crossover probability is 0.9, and mutation probability is 1/24.

4.2. Simulated analysis

4.2.1. Algorithm performance comparison

Figure 6 shows Pareto front end surface obtained by solving traditional NSGA-II and improved NSGA-II. According to the two optimization objectives set in Section 2.1, the search precision of Pareto front end surface obtained by solving traditional NSGA-II is better than that of traditional NSGA-II, which further improves the quality of the optimal solution set.
After using adaptive gene recombination operator, the simulation results of the above two algorithms are compared as shown in figure 7.

![Figure 7. Feasible solutions and evolutionary evolution generation of two algorithms](image)

Analysis and simulation results show that the number of feasible solutions to the improved NSGA-II population reaches the population size and remains stable after the number of iterations reaches 125 generations. The number of feasible solutions in the traditional NSGA-II population reaches the population size after 265 iterations and tends to be stable. Therefore, the improved NSGA-II can effectively overcome the problems of the traditional NSGA-II's slow speed and low search efficiency.

4.2.2. *The optimal eclectic charge-discharge strategy for the energy storage system*

Aiming at the problem that Pareto's optimal solution set contains a lot of information and it is difficult for operators to make decisions, the fuzzy clustering method is adopted to obtain the optimal eclectic charge-discharge strategy of the energy storage system, as shown in figure 8. The corresponding optimization results of the three energy storage charge-discharge strategies in the figure are shown in table 1.

![Figure 8. Optimal compromise operation strategy of energy storage system for two algorithms.](image)

**Table 1. Optimization result of two operation strategies.**

| Operation Strategy | Purchase cost from the grid /RMB | Grid side load variance /kW² |
|--------------------|---------------------------------|----------------------------|
| NSGA-II            | 3726                            | $2.4383 \times 10^5$        |
| Improved NSGA-II   | 3593                            | $1.9769 \times 10^4$        |

It can be seen from table 1 that, compared with the traditional NSGA-II, the daily purchase cost of the improved NSGA-II from the grid is reduced by 133 RMB, which further reduces the unnecessary operation cost of the charging station. The variance of side loads of the power grid was reduced by 18.92%, which improved the operation stability of the power grid.

5. **Conclusion**

Aiming at the problems of high operating cost of PV-integrated EV charging station and large fluctuation level of load on the side of power grid, the paper put forward a kind of based on adaptive
recombination operator to improve the NSGA - II. According to the MATLAB software simulation, the two optimization goals of the grid side load variance and the purchase cost from the grid during the operation of the energy storage system are calculated. By comparing the two algorithms, the following conclusions can be drawn:

- Compared with the traditional NSGA-II, the improved NSGA-II algorithm can better deal with the optimization operation of energy storage system with complex constraints. The improved NSGA-II algorithm has a higher accuracy in obtaining feasible solutions, and the population convergence rate is improved by 1.1 times, which overcomes the defects of the traditional NSGA-II algorithm.

- Compared with the traditional NSGA-II, in the charging and discharging strategy of the energy storage system obtained by using the proposed improved NSGA-II, the variance of side load of the power grid and the power purchase cost to the power grid are reduced. What’s more, the economic indexes of PV-integrated EV charging station and the technical indexes of power grid operation are further improved.

References

[1] Ministry of Science and Technology of the People's Republic of China (2012) The electric car "twelfth five-year" development of science and technology special planning. http://www.most.gov.cn/tztg/201204/W020120503407413903488.PDF.

[2] State Council of the People's Republic of China (2012) Energy Conservation and New Energy Automobile Industry Development Plan (2012-2020). http://www.gov.cn/zwgk/2012-07/09/content_2179032.htm.

[3] Xu Y., He C., Fu C., et al. (2019) Analysis of the Optimal energy storage Capacity configuration of optical storage power station under various scheduling modes. Acta Energiae Solaris Sinica, 40: 1632-1640.

[4] Guo Y.F., Gao H.L., Tian J. (2016) Photovoltaic output modeling by introducing clustering analysis and its application in reliability evaluation. Automation of Electric Power Systems, 40: 93-100.

[5] Wu X., Wang X.L., Li J., et al. (2013) A joint operation model and solution for hybrid wind energy storage systems. Proceeding of the CSEE, 33: 10-17.

[6] Chen Z., Chen Y.X., Che S.Y. (2019) Framework of integrated charging station for renewable energy vehical and energy optimal dispatching method. Automation of Electric Power Systems, 43: 41-51.

[7] Chen J., Wang C.S., Zhao B., et al. (2012) Economic operation optimization of a stand-alone microgrid system considering characteristics of energy storage system. Automation of Electric Power Systems, 36: 25-31.

[8] Wang S.X., Zhang S.T., Wang K., et al. (2020) Multi-objective optimal operation of distributed energy storage considering user demand response under time-of-use price. Electric Power Equipment, 40: 125-132.

[9] Zhang M.D., Song X.Z., Xin H.H., et al. (2013) Optimal operation strategy of battery energy storage system in distribution networks with consideration of power loss. Power System Technology, 37: 2123-2128.

[10] Wan J.H., Su H., Feng D.H., et al. (2020) Analysis and evaluation of the complementarity characteristics of wind and photovoltaic considering source-load matching. Power System Technology, 44: 3219-3226.

[11] Zhang M., Gao X., Lou W. (2007) A new crossover operator in genetic programming for object classification. IEEE Transactions on Systems, 37: 1332-1343.

[12] Alanis F.C.M., Rodriguez J.A.M.R. (2015) Self-calibration of vision parameters via genetic algorithms with simulated binary crossover and laser line projection. Optical Engineering, 54.
[13] Wirasingha S.G., Schofield N., Emadi A. (2008) Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility. 2008 IEEE Vehicle Power and Propulsion Conference, 1-8.

[14] Grobler J., Engelbrecht P.A. (2018) Arithmetic and parent-centric headless chicken crossover operators for dynamic particle swarm optimization algorithms. Soft Computing, 22.

[15] Ronco C.C.D., Benini E. (2013) A Simplex Crossover based evolutionary algorithm including the genetic diversity as objective. Applied Soft Computing Journal, 13.

[16] Liu Q., Liu X., Wu J., et al. (2019) An Improved NSGA-III Algorithm Using Genetic K-Means Clustering Algorithm. IEEE Access, 7:185239-185249.

[17] Xiao H., Pei W., Kong L. (2017) Multi-objective optimization scheduling method for active distribution network with large scale electric vehicles. Transactions of China Electrotechnical Society, 32: 179-189.

[18] Wirasingha S.G., Schofield N., Emadi A. (2008) Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility. 2008 IEEE Vehicle Power and Propulsion Conference, 1-8.

[19] Shanghai Municipal Electric Power Company. (2017) Shanghai power grid sales price. http://sh.bendibao.com/cyfw/2015526/132966.shtm.