An Electric Vehicle Charging Station Service Strategy Based on Logistic Model

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Abstract. In order to improve the charging service quality of electric vehicle charging station (EVCS) and the charging efficiency of electric vehicles (EVs), this paper proposed M/M/k/N queuing theory model for limited capacity charging station, improved the arrival rate of EVs to be charged with the logistic model, and then introduced a synchronization-mutual exclusion mechanism in the two processes of queuing waiting and charging service after EVs entering a station, thereby avoiding resource conflicts, ensuring the charging service process to be a certain order. Finally, through the experimental simulation, we compared the M/M/k/N model proposed in this paper with the traditional M/G/k model, which proved our modified model can effectively reduce the average waiting time and the charging service time. In addition, it is verified the existence of the logistic growth model and the significance of the synchronization-mutual exclusion mechanism.

1. Introduction

As a kind of new energy vehicle, EVs have the advantages of low pollution, simple structure and convenient maintenance etc, however, China's EV industry still has the universality to be solved: the total amount of charging infrastructure is insufficient, the utilization rate is low, the layout is unreasonable, and the charging mode is incompatible [1]. The data also mentioned that the utilization rate of China's public charging infrastructure is only 12%, the low charging service efficiency is one of the main reasons [2]. How to make reasonable charging plans and efficient charging service strategies for EVs and EVCSs have become the key link in the problem of EV charging. The queuing theory which applied to analyse the charging station queueing system, to derive the queue service indicators, and to realize the rational usage of charging facilities has been the research hotspot of many scholars on the topic of “charging station facility planning” [3,4].

The literature [5] used the M/G/k queuing model as the basis and compared it with the M/M/k queuing model, they proved the two are not universal in the electric taxi charging station queueing system; the reference [6] considered the customer's impatience and walking for the limited capacity of a queuing model, but the dynamic changes of the arrival rate about EVs is ignored.

Through the analysis of existed research work, it’s found that the charging service research of charging stations mostly focuses on M/M/k and M/G/k model or their variants[7,8]. The determination of the model is generally based on the linear fitting or assumption proof, but the arrival rate of EVs all assumed to be a constant [9,10]. While in actual life, the rate often depends on the state of the system at different moments to change, which meets the characteristic of the logistic growth. What’s more, there is no mechanism to ensure the processes of queueing waiting and charging service to execute
orderly. So, in this paper, we established a charging service strategy by M/M/k/N model. To be closer to reality and avoid oversaturation of the charging station, the charging station is regarded as a limited capacity, and the queue service indicators are obtained through mathematical derivation. Under the analysis of the arrival rate for EVs to be charged, we found that the speed increase of it satisfies the law of logistic growth in a certain stage. Therefore, we improved the logistic growth model and applied to the arrival rate function. Finally, the synchronization-mutual exclusion mechanism is added to the process, we verified the effectiveness of it by the experimental simulation.

The main contributions of this paper are as follows:

1. Based on the traditional M/M/k and M/G/k queuing theory models, an improved M/M/k/N model is proposed, which reduces the average waiting time and the charging service time for EVs to some extent.

2. We improved the arrival rate of EVs by the logistic growth effect and proved the charging process to meet the Markov property, with the support of Markov state transition probability, we obtained the queue service indicators, which provide effective foundations for EVs to choose a reasonable charging queue and charging amount.

3. In the processes of queuing waiting and charging service after EVs entering the charging station system, a synchronization-mutual exclusion mechanism is introduced. The simulation experiment compared the desired variance of the system on the charging service time before and after the mechanism is added. It is verified that the mechanism can be effectively enhanced the system stability.

2. Charging Station Service Strategy

2.1. Queuing Model

A queuing structure usually consists of three indicators: the number of queues, the number of service desks, and the number of service phases [11]. In the research scenario of this paper, when a vehicle to be charged arrives, if the total number of EVs existed in the current station is less than \( N \), the vehicle is allowed to enter and select the required charging mode \( \text{opt} \) (0: DC fast charging; 1: AC slow charging) and charging amount \( \text{ca} \) (0: 80% \( C \); 1: 100% \( C \)), where \( C \) represents the battery capacity of the EV. After that, if there is an idle charging pile under the corresponding selection, the vehicle can directly drive to the pile for charging, and the charging service time obeys the exponential distribution with the parameter \( \mu \); otherwise it needs to wait in line, waiting time is no clear limit. When the total number of EVs in the station is greater or equal to \( N \), it means that the system is full, the charging station no longer allows any vehicles to enter. Above all, the queuing structure is a single charging service mode of multiple queues under multiple service desks, the number of service desks refers to the number of charging piles. This paper has a total of \( k \) AC and DC charging piles, of which \( m \) DC charging piles, and \( (k-m) \) AC charging piles, the number of DC charging piles is greater than AC charging piles; single service refers to the steps of service work, that is, the charging service steps that EVs need to go through. This article only contains a service step for charging following the principle of fairness, adopting the principle of “first come, first served” (FCFS). The queuing system diagram of this paper is as follows:

![Queueing System Diagram](image)

**Figure 1.** Queueing system diagram.

In the M/M/k/N queuing model of this paper, each item is expressed as: the arrival time interval is subject to a negative exponential distribution based on Markov process/the charging service time is subject to a negative exponential distribution based on Markov process/the number of charging...
EVs to be charged successively arrive at the charging station with the system capacity $N$, obeying the Poisson distribution with the arrival rate of $\lambda$, in other words, the time interval of the single vehicle to be charged obeys the negative exponential distribution with the parameter $\lambda$, and the probability density function is as follows:

$$f(n) = \begin{cases} \frac{1}{\lambda} e^{-\frac{n}{\lambda}}, & n \geq 0 \\ 0, & \text{else} \end{cases}$$

(1)

### 2.2. Improved Logistic Growth Model

In the actual application scenario, the vehicle arrival rate changes with the state of the number of different vehicles in the system, and is not a constant. The EVs driving on the road is connected to the EVCS system by means of the vehicle system, and dynamically grasps the corresponding charging station at a specific moment about the idle situation. When a charging station is relatively idle, it will attract more EVs to come to charge, so that the arrival rate of the station will rise significantly; conversely, when the number of vehicles in a charging station is approaching the capacity limit, the subsequent EVs will not be willing to arrive, it is inevitable to cause the arrival rate of this charging station to drop. Therefore, the logistic effect in this paper is mainly reflected in the growth rate of the vehicle arrival rate $\lambda$, the derivation of the logistic model refers to [12], so that $r$ decreases as the number of vehicles $n$ at the time $t$ in the station increases. If $r$ is expressed as a function $r(n)$ of $n$, then the function should be a subtraction function, recorded as:

$$\frac{dn}{dt} = r(n)n, n(0) = n_0$$

(2)

Assuming that the function $r(n)$ is a linear function of $n$, i.e.

$$r(n) = r - sn, r > 0 \text{ and } s > 0$$

(3)

Where $r$ is the inherent growth rate, indicating the arrival rate of growth when the number of vehicles in the station is small (theoretically $n=0$). When $n=N$, the vehicle no longer arrives, $r(N)=0$ at that time. Substituting it into (3) gives $s=r/N$, so there is

$$r(n) = r\left(1 - \frac{n}{N}\right)$$

(4)

Substituting equation (4) into equation (2),

$$\frac{dn}{dt} = rn\left(1 - \frac{n}{N}\right), n(0) = n_0$$

(5)

The factor $rn$ at the right of the above formula reflects the growth trend of the number of EVs themselves, the factor $(1-n/N)$ reflects the logistic effect on the number of EVs arriving. The larger $n$ is, the larger the former factor is, the smaller the latter factor is, which indicates that the increase in vehicle arrival rate is the result of the synergy between the two factors. The growth rate $dn/dt$ is denoted as $h(n)$, and the vehicle arrival rate $\lambda$ and the charging station service rate $\mu$ are defined as follows:

$$\lambda(n) = \left[1 + h(n)\right]\lambda_0, n \leq N$$

(6)

$$\mu^{opt}(n) = \begin{cases} \mu_0, n \leq k < N \\ \left(\frac{n}{k}\right)\mu_0, k \leq n \leq N \end{cases}$$

(7)

Among them, when $opt=0$, there is

$$\mu^0(n) = \begin{cases} \mu_0, n \leq m < N \\ \left(\frac{n}{m}\right)\mu_0, m \leq n \leq N \end{cases}$$

(8)

when $opt=1$, there is

$$\mu^1(n) = \begin{cases} \mu_0, n \leq k-m < N \\ \left(\frac{n}{k-m}\right)\mu_0, k-m \leq n \leq N \end{cases}$$

(9)

In formula (7), $\mu^{opt}(n)$ represents the service rate of the charging station in the state of $n$ vehicles in different charging modes, when $n \leq k < N$, indicates that there is an idle charging pile in the station.
the charging service time is served by the intrinsic service rate \( \mu_0 \); when \( k \leq n \leq N \), it means that there is no idle charging pile in the station, the EV needs to be queued for charging, at this time, the service rate is proportional to the total number of EVs in the station when the number of charging piles is constant. See (8)(9) for the formula.

2.3. Queue Service Indicators Under the Markov Birth and Death Process

The process of the birth and death is widespread in the queuing theory system and is a special kind of stochastic process [13]. Let \( N(t) \) denote the number of EVs in the system at time \( t \), because the arrival time interval of the EV and the charging service time are independent from each other, and distributed in the exponential distribution, so the process \( \{N(t),t \geq 0\} \) is satisfied the stochastic process of Markov chain [13], the state space is \( I'=\{0,1,2,\ldots,n\} \), if the process satisfies the following conditions simultaneously:

\[
P_{0i}(t) = \lambda_0 t + o(\Delta t), \lambda_i > 0
\]
\[
P_{ij}(t) = \mu t + o(\Delta t), \mu_i > 0
\]
\[
P(\Delta t) = 1 - (\lambda_i + \mu_j) \Delta t + o(\Delta t).
\]
\[
P_{ij}(\Delta t) = o(\Delta t), |i-j| \geq 2
\]

(10)

Then the process \( \{N(t), t \geq 0\} \) is the birth and death process, where \( \lambda_i \) is the birth rate, in this paper, is referred to the arrival rate of EVs, \( \mu_i \) is the death rate, this article refers that EVs leave after charging with the charging service rate \( \mu \).

\[
P_0 = (\mu_0, \lambda_0, \lambda_0, \lambda_0, \lambda_0)
\]

(11)

formula(11) is the one-step transition probability for the Markov chain, which indicates the probability can be simply referred to the state \( i \) at time \( t \) to the state \( j \) at time \( t+\Delta t \), as transition probability, the corresponding Markov state transition probability matrices is as follows:

\[
P = \begin{bmatrix}
-\lambda & 0 & \cdots & 0 & 0 \\
\mu & -\lambda & 0 & \cdots & 0 \\
0 & \mu & -\lambda & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & \cdots & -\lambda \\
0 & 0 & \cdots & \cdots & -\lambda
\end{bmatrix}
\]

(12)

Therefore,

\[
\mu P_0 = \lambda P_0
\]

(13)

The values of \( \lambda \) and \( \mu \) are obtained in equation (6)(7), and the difference equation is solved to obtain the state transition probability as follows:

\[
P_0 = \left[ \sum_{i=0}^{N-1} \left( \begin{array}{c}
\lambda \\
\mu
\end{array} \right)^i \frac{1}{k! \mu (1-\alpha)^i} \int_{i+1}^{\infty} P_\alpha d\lambda \right] P_{00}, 0 \leq n \leq k
\]

(14)

\[
P_0 = \left[ \frac{1}{n \mu} P_0, 0 \leq n \leq k
\]

\[
P_0 = \left[ \frac{1}{k! \mu (1-\alpha)^i} \int_{i+1}^{\infty} P_\alpha d\lambda \right] P_{00}, k+1 \leq n \leq N
\]

(15)

Where \( \alpha = \lambda / k\mu \) is the average service strength, \( \alpha < 1 \) avoids forming an infinite queue, \( i \) is the number of random variables, i.e. the number of charging piles, \( i=0,1,2,\ldots,k-1 \). According to the above formula, several service indicators can be obtained:

1. Average queue length, that is the number of EVs waiting to be charged,

\[
ML_q^+ = \frac{(k\alpha)^n \alpha}{k! (1-\alpha)^i} P_0
\]

(16)

Among them, when \( opt=0 \), there is

\[
ML_q^+ = \frac{(n\alpha)^n \alpha}{m! (1-\alpha)^i} P_0
\]

(17)
when $\text{opt}=1$, there is

$$ML_{..}^2 = \frac{(k-a)^{\alpha} - a}{(k-a)(1-\alpha)} P$$

(18)

2. The number of EVs staying at the charging station is the average queue length plus the average number of EVs receiving charging service, i.e.,

$$ML_{..}^P = ML_{..}^{\text{opt}} + P = ML_{..}^{\text{opt}} + \frac{\lambda}{\mu}, \forall \text{opt} : \text{opt} = 0,1$$

(19)

3. Average waiting time is

$$MT_{..}^{\text{opt}} = \frac{ML_{..}^{\text{opt}}}{\lambda}, \forall \text{opt} : \text{opt} = 0,1$$

(20)

when $\text{opt}=0$, there is

$$MT_{..}^0 = \frac{\mu}{\lambda(\mu^2 - \lambda)}$$

(21)

when $\text{opt}=1$, there is

$$MT_{..}^1 = \frac{\mu^2}{\lambda(\mu^2 - \lambda)}$$

(22)

4. Average charging service time is

$$MT_{..}^{\text{opt}} = \frac{ML_{..}^{\text{opt}}}{\lambda}, \forall \text{opt} : \text{opt} = 0,1$$

(23)

when $\text{opt}=0$, there is

$$MT_{..}^0 = MT_{..}^{\text{opt}} + \frac{\lambda}{\mu^2}$$

(24)

when $\text{opt}=1$, there is

$$MT_{..}^1 = MT_{..}^{\text{opt}} + \frac{1}{\mu^2}$$

(25)

2.4. Charging Selection Strategy

(1) Selection of charging mode

According to the charging mode of the charging pile, it can be divided into DC charging pile, AC charging pile and AC-DC integrated charging pile. For the sake of simplicity of research, this paper assumed the charging mode is the first two. The DC charging speed is fast, also known as "fast charging", but the damage to the battery is large. While the AC charging speed is slow, commonly known as "slow charging", but it is environmentally friendly and good for battery maintenance. Because the two modes have their own advantages and disadvantages, users can make the choice according to their own conditions. The system model proposed in this paper requires the user to select the required charging mode as soon as being allowed to enter the charging station.

(2) Choice of charging amount

Due to realistic factors such as battery safety and power life loss, battery maximum charging amount is not equal to C, and can only be close to C. The battery charging capacity of EVs is very fast at the first 80%, after that, especially when it is close to the maximum capacity of the battery, the speed is slower and slower, showing a certain degree of "marginal effect" [14], so the recommended target charging amount is usually about 80% C. In this paper, when the EV completes the charging mode selection, the user also needs to select the desired charging amount.

2.5. Synchronization-Mutual Exclusion Mechanism

For the related concepts of the process synchronization, mutual exclusion, semaphore and P, V operations, please refer [15]. In this paper, when the EV is allowed to enter for charging service, each EV waiting to be charged is regarded as a process, $k$ charging piles are regarded as $k$ critical resources, the parallel charging service is executed independently of each other without interference. After the EV to be charged enters, a series of actions must be performed in sequence. Firstly, select the charging mode and the charging amount, then come to the corresponding charging pile waiting in line or charging
directly, the process can be seen as process synchronization. When each of \( k \) charging piles is in charging service, the back EVs can only wait in line until the previous EV is charged completed and leave the charging pile, which can be regarded as mutual exclusion. The EVCS system flow chart as follows:

![Figure 2. Charging station system flow chart.](image)

If the charging mode selection as the process OPT, the desired charging amount as CA, the vehicle performs the charging recording process R, there existing pseudo codes as follows:

**Pseudo Codes:** Synchronization-Mutual Exclusion Mechanism

**Variable Definitions:** Semaphore S, option, capacity, charge, complete;

**Process:**

S=N;

Process EV i( ) /* i=1, 2, …, n */

{P(S);

Process OPT( ) /* opt selection */

{while(1)

{P(option);

Select charging mode ( );

V(capacity);}}

Process CA( ) /* ca selection */

{while(1)

{P(capacity);

Select the desired amount of charge ( );

V(option);

Waiting in line or going to the idle charging pile ( );

P(charge);

V(complete);}}

Process R( ) /* the EV is charging in the corresponding mode */

{while(1)

{P(complete);

Charging and achieving the desired amount of charging ( );

V(charge);

Charging ends, leaving the charging station ( );}}

V(S);}
3. Experimental Simulation and Evaluation

Based on the Matlab-R2016a, simulation experiments of M/M/k/N and traditional M/G/k models are carried out. The system parameters are set as shown in the following Table 1:

| Parameter item                  | Parameter value |
|--------------------------------|-----------------|
| system capacity *N*             | 50; 100         |
| number of charging piles *k*    | 20; 35          |
| number of DC charging piles *m* | 15; 20          |
| initial arrival rate *Λ₀*       | 15              |
| initial charging service rate *μ₀* | 1.2            |
| inherent growth rate *r*        | 0.8             |

The arrival rate of the EV to be charged and the charging service rate respectively generated by the probability distribution mentioned in the M/M/k/N model of this paper and the traditional M/G/k model, the EV selects charging mode and desired charging amount according to the probability of Table 2:

| probability *P* | 0       | 1       |
|-----------------|---------|---------|
| *ca*            | 0.6     | 0.4     |
| *opt*           | 0.8     | 0.2     |

Then, according to the formulas (20), (23), obtained the waiting time and the charging service time, then calculated the mean values for 50 iterations, where in the charging service time (the waiting time +the charging time). The results are shown in Figure 3 and Figure 4.

By comparing with the traditional M/G/k model, under the case of the same parameters, when *N*=50, with the increasing number of EVs, the M/M/k/N model is significantly lower than another model in terms of average waiting time and charging service time. This indicates to some extent that our model has achieved some improvements in the charging service for EVs.

For the verification of the logistic effect, this paper simulated in the environment of system scale 50 and 100 respectively, and contrasted the actual EV arrival data among a certain time period in a commercial area of Beijing as the benchmark, we compared the expected value of EV arrival rate with model M/M/k/N that introduced the logistic factor before and after. Here, one of the experimental results is taken as an example, where *N*=100, *k*=35, *m*=20, the result is shown in Figure 5:
Figure 5. The expectation of EVs arrival rate. Figure 6. The variance of charging service time.

For Figure 5, when no logistic factor is introduced, with the increase of the number of EVs in the station, it won’t have any influence on the arrival of following vehicles, within a certain number of EVs, the growth rate has a nearly linear upward trend, when reached 100, the arrival rate drops rapidly, because the system no longer allows any EVs to be in; once the logistic effect is introduced, when the number of EVs is less than 35 (the total number of charging piles), there is no need to wait in line, the waiting time is short, so the arrival rate of other EVs increases rapidly. Along with the increasing number of EVs, the waiting time is prolonged, the arrival rate of followings is significantly reduced, later gradually stabilized. After a period of time, as the number of EVs is getting closer to the system capacity, the logistic effect is further strengthened, the following EVs almost no longer arrive at the station. By comparing with the actual value, it can be seen that the model introduced the logistic factor is closer to it.

As for the verification of the synchronization-mutual exclusion mechanism, this paper chose to conduct its own comparison experiment. The parameters are set to $N=50$, $k=20$, $m=15$, the $M/M/k/N$ model took the mean of the generated charging service time and calculated the variance in the presence and absence of the mechanism. The experimental chart obtained as Figure 6. By introduced the synchronization-mutual exclusion mechanism, in the case where other conditions are unchanged, since unnecessary resource conflicts are avoided, the sequential execution of the charging service steps is guaranteed, the system fluctuation get smaller and the stability is higher.

4. Conclusion

In this paper, an EVCS service strategy based on $M/M/k/N$ queuing theory model with limited capacity is proposed. In addition, to be closer to the actual application scenario, we analyzed and modeled the logistic arrival rate function of EVs, and also got the queue service indicators under the Markov process. What’s more, for the problems of charging pile resource preemption and charging service step execution confusion, the synchronization-mutual exclusion mechanism is added to the EVCS system. Through the simulation experiment, the model and related strategies proposed in this paper are verified and compared, which further proved that our service strategy of EVCS based on logistic effect has certain research value and feasibility.

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