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(54) Title: METHOD FOR EVALUATING ACCEPTANCE CAPABILITY OF ELECTRIC VEHICLE IN URBAN DISTRIBUTION NETWORK

(54) 发明名称： 城市配电网对电动汽车的接纳能力评估方法

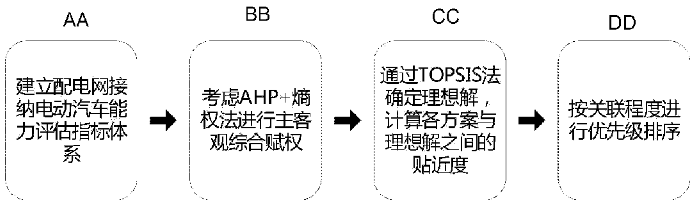

图 1

AA Set up an acceptance capability evaluation index system for an electric vehicle in a distribution network
BB Consider an AHP and an entropy weight method to perform subjective and objective comprehensive weighting
CC Determine an ideal solution by means of a TOPSIS, and calculate the closeness between each solution and the ideal solution
DD Sort priorities according to association degrees

(57) Abstract: A method for evaluating the acceptance capability of an electric vehicle in a urban distribution network, comprising the following steps: 1) on the basis of a trip-chaining theory and a Monte Carlo method, performing electric vehicle charging load prediction on an electric vehicle charging load space-time distribution in a target area; 2) by taking into consideration the rationality, reliability and economy of a distribution network, setting up a comprehensive acceptance capability evaluation index system; 3) proposing an analytic hierarchy process (AHP) and entropy weight method-based comprehensive weighting method for evaluation indices, and using a technique for order of preference by similarity to ideal solution (TOPSIS) to evaluate the acceptance capability of the distribution network when the charging load is accessed in different ways; and 4) by taking a typical IEEE33 standard distribution network as an example for simulation, analyzing the space-time distribution of the charging load in the target area and the impact thereof on the distribution network. Simulation results show that when selecting some nodes of the distribution network to access electric vehicles in an appropriate amount, the closer the evaluation indices are to an ideal point, and the better the acceptance capability under the aforementioned solution.

(57) 摘要： 一种城市配电网对电动汽车的接纳能力评估方法，包括以下步骤：1)基于出行链理论和蒙特卡洛方法对目标区域内的电动汽车充电负荷时空分布进行了电动汽车充电负荷预测；2)考虑配电网运行合理性、可靠性以及经济性，构建了全面的接纳能力评价指标体系；3)提出了基于层次分析法(AHP)和熵权法的评估指标综合赋权方法，并利用理想点逼近法(TOPSIS)对以不同方式接入充电负荷时的配电网接纳能力进行评估；4)以典型IEEE33标准配电网为例进行仿真，分析了目标区域内充电负荷的时空分布及其对配电网的影响。经仿真结果显示，当选择配电网部分节点适量接入电动汽车时各项评估指标与理想点的贴近度越近，该方案下的接纳能力越好。

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METHOD FOR EVALUATING HOSTING CAPACITY OF URBAN DISTRIBUTION NETWORK FOR ELECTRIC VEHICLE

TECHNICAL FIELD

[01] The present disclosure relates to the research field of charging load modeling of an electric vehicle and an influence of a charging load on a distribution network, and in particular, to a method for evaluating a hosting capacity of an urban distribution network for an electric vehicle.

BACKGROUND

[02] With increasingly serious energy and environmental problems, electric vehicles with advantages of high efficiency and cleanliness have been vigorously promoted by governments all over the world. However, due to a random and aggregated spatio-temporal distribution of charging loads of electric vehicles, large-scale connection of electric vehicles will impose an adverse influence on safe and economic operation and power quality of a distribution network, which is mainly reflected in line overloading, transformer overload, power device aging, voltage drop, harmonic pollution, and system loss increase. Due to different nodes to which electric vehicles are connected in the distribution network and different quantities of electric vehicles, an influence on the distribution network is different under different connection scenarios. Therefore, it is necessary to evaluate a hosting capacity of the distribution network for the electric vehicles, which has also become an important premise for further promoting the electric vehicles.

[03] In previous studies, when indexes for evaluating the hosting capacity for the electric vehicles are selected, whether a node voltage level exceeds a threshold, a load ratio of a distribution transformer, whether a line power flow exceeds a safety constraint, a network power loss, and other factors are usually considered. These studies focus on comprehensive evaluation of an evaluated object, put forward seven indexes for evaluating a carrying capability of the distribution network from technical rationality, safety and reliability, and economical efficiency, and combine a fuzzy theory with an analytic hierarchy process (AHP) to form a fuzzy AHP for multi-target decision-making, so as to evaluate carrying capabilities of the distribution network in different schemes. This method is a common evaluation method in engineering. However, the indexes for evaluating the hosting capacity of the distribution network for the electric vehicles cannot be selected comprehensively, and index weights are subjective, which will cause a certain deviation to an evaluation result.

[04] Therefore, the present disclosure proposes a method for evaluating, based on a technique for order preference by similarity to an ideal solution (TOPSIS), a hosting capacity of a distribution network for an electric vehicle, to establish an evaluation index system from rationality, safety, and economical efficiency of operation of the distribution network, and comprehensively evaluate the hosting capacity of the distribution network. The TOPSIS is used to evaluate the hosting capacity of the distribution network for the electric vehicle. A comprehensive weighting method obtained by using an entropy weight method to modify AHP is used to weight each evaluation index. Finally, the hosting capacity of the distribution network for electric vehicles that are connected in different manners is simulated and analyzed with the help of an IEEE33-compliant standard distribution network model.

SUMMARY

[05] Based on evaluation of a hosting capacity of a traditional distribution network, six evaluation indexes are selected based on rationality, safety, and economical efficiency: a ratio that a voltage offset does not exceed a threshold, a ratio that reactive power of a node fails to reach a standard, a safe network operation index, a load ratio, a network loss value, and an additional reactive power cost. A hosting capacity evaluation method of a TOPSIS is used to normalize indexes in an original multi-attribute decision matrix. Based on an index sequence, an optimal index value is selected to form a positive ideal solution, and a worst index value is selected to form a negative ideal solution. Then, a proximity to an ideal value is measured based on nearness degrees between each scheme and the positive and negative ideal solutions, and the scheme is sorted based on the nearness degrees, to evaluate a hosting capacity of a distribution network when a charging load is connected in different manners.

[06] The present disclosure has the following advantages over the prior art.

[07] 1. The TOPSIS is used to evaluate the hosting capacity of the distribution network when the charging load is connected in different manners. Based on evaluation of the hosting capacity of the traditional distribution network, all-round comprehensive evaluation indexes are selected, covering the rationality, safety, and economical efficiency. In this way, the hosting capacity of the distribution network can be accurately evaluated in an all-round way.

[08] 2. As a subjective weighting method, an AHP can combine a qualitative concept and quantitative data. The AHP compares an influence of each index on an upper-level index by using an established index system, to form a determining matrix of a current level, and then performs a same influence determining process on a lower level till the bottom level. A weight of each index is calculated by obtaining a maximum eigenvalue of the determining matrix and its corresponding eigenvector.

[09] 3. An objective weighting method, namely, an entropy weight method, is introduced. This method defines value and a weight of data based on an original dispersion degree of the data. Information is a measure of an order degree of the system, and entropy is a measure of a disorder degree of the system. Smaller information entropy of each index leads to a greater amount of information contained in the index, greater value of the index in an evaluation process, and a higher weight given to the index.

BRIEF DESCRIPTION OF THE DRAWINGS

[010] FIG. 1 shows a framework for evaluating a hosting capacity of a distribution network for an electric vehicle according to the present disclosure;

[011] FIG. 2 is a diagram of an evaluation index system of a hosting capacity of a distribution network according to a present disclosure;

[012] FIG. 3 shows a charging load curve of each area under a hybrid chain according to the present disclosure;

[013] FIG. 4 shows a topology of an IEEE33-compliant distribution network according to the present disclosure; and

[014] FIG. 5 shows node voltage levels of a charging load of an electric vehicle in different connection schemes according to the present disclosure.

DETAILED DESCRIPTION

[015] The present disclosure is described below in detail with reference to a diagram of a hosting capacity evaluation framework, a diagram of an evaluation index system, and specific embodiments.

[016] The present disclosure provides a TOPSIS-based method for evaluating a hosting capacity of a distribution network for an electric vehicle, including the following steps.

[017] (1) Perform charging load modeling for an urban electric vehicle based on a trip chain and a Monte Carlo method.

[018] 1) Generating a trip chain model

[019] The present disclosure adopts a trip chain theory to study a spatio-temporal trip trajectory and a trip characteristic of the electric vehicle. A start point and an end point of the trip chain proposed in the present disclosure mainly include a residential area, a work area, a commercial area, a recreational area, and other areas, which are represented by H, W, C, R, and O respectively. It is assumed that a start point of a first trip of a user is the residential area, t_0 represents start time of the trip, $t^{\mathrm{d}}_{s_i \to d_i}$ represents driving time of the user from a start point s_i to an end point d_i, $t^{\mathrm{p}}_{d_i}$ represents dwell time at a destination d_i, and $s^{\mathrm{d}}_{s_i \to d_i}$ represents a driving distance of an i^{th} trip. G_{TC} represents a spatio-temporal trip characteristic quantity set of the electric vehicle, which may be described as the following formula (1):

$$G_{\mathrm{TC}} = \{s_i, d_i, t_0, t^{\mathrm{d}}_{s_i \to d_i}, t^{\mathrm{p}}_{d_i}, s^{\mathrm{d}}_{s_i \to d_i}\} \quad (1)$$

$$i \in \{1,2,3,4,5\}; s_i, d_i \in \{\mathrm{H,W,C,R,O}\}$$

[020] 2) Power consumption of the electric vehicle

[021] The present disclosure simplifies the power consumption of the electric vehicle, ignores an influence of a driving habit of the user and an external factor on battery power consumption of the vehicle in an actual driving process, and considers that the battery power consumption has a linear relationship with a driving mileage of the vehicle. The battery power consumption of the vehicle in the driving process and a battery capacity when the vehicle reaches the destination can be determined according to the following formulas (2) to (4):

$$\Delta E_{s_i \to d_i} = s^{\mathrm{d}}_{s_i \to d_i} \cdot e_0 \quad (2)$$

$$E_{d_i} = E_{d_{i-1}} - \Delta E_{s_i \to d_i} \quad (3)$$

$$\mathrm{SOC}_{d_i} = (E_{d_{i-1}} - \Delta E_{s_i \to d_i}) / B_{\mathrm{ev}} \quad (4)$$

[022] In the above formulas, e_0 represents power consumption of the electric vehicle in a unit mileage, $\Delta E_{s_i \to d_i}$ represents total power consumption of the vehicle driving from s_i to s_i,

B_{ev} represents a battery capacity of the vehicle, E_{d_i} represents a remaining battery capacity of the electric vehicle when the electric vehicle reaches the destination *i*, and SOC_{d_i} represents a state of charge (SOC) of the electric vehicle when the electric vehicle reaches the destination *i*.

[023] 3) Establishing a charging decision model of the electric vehicle user and calculating a charging load

[024] Based on a capacity and an SOC of a battery at a current location of the electric vehicle user, if a remaining SOC cannot meet an electricity demand of a next journey, charging needs to be performed in time, or if the SOC is relatively sufficient, a charging plan may be made based on a current charging demand.

[025] The Monte Carlo method is used to establish a model for all electric vehicles in a target area, adopt different charging decisions for users with different charging demands, and take statistics on charging time and charging loads of the users, to obtain a total spatio-temporal charging demand distribution.

[026] (2) Establish a system for evaluating a hosting capacity of a distribution network for the electric vehicle.

[027] The present disclosure considers an influence of connection of the electric vehicle on the distribution network based on charging load modeling of the electric vehicle, establishes an index system from rationality, safety, and economical efficiency based on an operation evaluation research on a traditional distribution network, and performs comprehensive evaluation on the hosting capacity of the distribution network.

[028] To reflect objectivity and rationality of the method, the present disclosure performs comprehensive weighting on a plurality of indexes in different decision schemes by combining an AHP and an entropy weight method. Finally, the TOPSIS is used to evaluate a hosting capacity of the distribution network when the charging load is connected in different manners. A hosting capacity evaluation framework is shown in FIG. 1. Based on evaluation of the hosting capacity of the traditional distribution network, six evaluation indexes are selected based on rationality, safety, and economical efficiency, as shown in FIG. 2.

[029] 1) Ratio T_1 that a voltage offset does not exceed a threshold

[030] The ratio T_1 that the voltage offset does not exceed the threshold is a ratio of a quantity of nodes whose voltages do not exceed the threshold in the distribution network to a total quantity of nodes after the charging load of the electric vehicle is connected to the distribution network. This index is used to evaluate whether a voltage offset of each node meets a relevant technical standard after the charging load of the electric vehicle is connected. In the present disclosure, a valid node voltage ranges from 0.9 to 1.1.

$$T_1 = \frac{N_v}{N} \times 100\% \quad (5)$$

[031] In the above formula, N_v and N respectively represent a quantity of nodes meeting a voltage offset standard in the distribution network and a total quantity of system nodes.

[032] 2) Ratio T_2 that reactive power of a node fails to reach a standard

[033] The ratio T_2 that the reactive power of the node fails to reach the standard is a ratio of a quantity of nodes whose power factors cannot meet a required reactive power configuration standard to the total quantity of nodes after the charging load of the electric vehicle is connected to the distribution network. This index is used to evaluate whether reactive power of each node meets the standard after the charging load of the electric vehicle is connected. In the present disclosure, a standard range of a node power factor is set to 0.85 to 1.

$$T_2 = (1 - \frac{N_q}{N}) \times 100\% \quad (6)$$

[034] In the above formula, N_q and N respectively represent a quantity of nodes meeting a reactive power standard in the distribution network and the total quantity of nodes.

[035] 3) Safe network operation index S_1

[036] The safe network operation index S_1 indicates a ratio of a quantity of lines whose current values exceed safe carrying capacities of these lines to a total quantity of lines after the charging load of the electric vehicle is connected to the distribution network. This index is used to evaluate whether a single circuit line in the network meets a safe operation standard after the charging load is connected.

$$S_1 = \frac{L_{out}}{L} \times 100\% \quad (7)$$

[037] In the above formula, L_{out} and L respectively represent a quantity of lines whose currents exceed a maximum current range for safe operation in the distribution network and the total quantity of lines.

[038] 4) Load ratio S_2

[039] The load ratio S_2 is a ratio of short-term average load of a distribution transformer or line to maximum load after the charging load of the electric vehicle is connected to the distribution network. This index is used to evaluate a short-term influence on safe operation of the distribution network after the charging load is connected.

$$S_2 = \frac{P_{av}}{P_{\max}} \times 100\% \quad (8)$$

[040] In the above formula, P_{av} and $P_{\max}$ respectively represent the short-term average load and the generated maximum load in the distribution network.

[041] 5) Network loss value E_1

[042] The network loss value E_1 is a sum of an active power loss of each line after the charging load of the electric vehicle is connected to the distribution network. This index is used to evaluate an economical influence on operation of the distribution network after the charging load is connected.

$$E_1 = \sum (P_i^2 + Q_i^2) \cdot \frac{R_i}{U_i^2} \quad (9)$$

[043] In the above formula, P_i and Q_i respectively represent active power and reactive power of a line i, R_i represents resistance of the line i and its connected device, and U_i represents a voltage of the line i.

[044] 6) Additional reactive power cost E_2

[045] The additional reactive power cost E_2 is an additional cost incurred by reactive power compensation performed to ensure that a power factor is relatively reasonable after the charging load of the electric vehicle is connected to the distribution network. This index is used to evaluate an additional investment required to perform reactive power compensation for each node in the distribution network due to an insufficient power factor.

$$E_2 = \eta \cdot Q_{need} \quad (10)$$

[046] In the above formula, η represents a necessary investment for reactive power compensation per unit capacity, Q_{need} represents a required reactive power compensation capacity after the charging load of the electric vehicle is connected, and η is set to 0.01 万元/kvar in this specification.

[047] (3) Study a TOPSIS-based hosting capacity evaluation method.

[048] The present disclosure normalizes an index matrix of an evaluation scheme; measures a proximity to an ideal value by using a Euclidean distance, and performs comprehensive evaluation based on a gray correlation degree describing a degree of closeness between evaluated objects, a group utility value measuring an overall nearness degree between each scheme and an ideal solution, and an individual deviation value describing a deviation degree of a worst index in each scheme; and prioritizes a hosting capacity in the scheme based on a comprehensive evaluation standard.

[049] 1) Constructing a weighted normalized matrix

[050] A decision matrix X is normalized according to the following formulas (11) to (13), a comprehensive weight of the above comprehensive indexes is multiplied by a normalized decision matrix to obtain a weighted normalized matrix Y:

$$b_{ij} = \frac{a_{\max,j} - a_{ij}}{a_{\max,j} - a_{\min,j}} \quad (11)$$

$$b_{ij} = \frac{a_{ij} - a_{\min,j}}{a_{\max,j} - a_{\min,j}} \quad (12)$$

$$b_{ij} = \begin{cases} 1 - \dfrac{q_1 - a_{ij}}{\max(q_1 - \min(a_{ij}), \max(a_{ij}) - q_2)}, & a_{ij} < q_1 \\ 1 & , q_1 < a_{ij} < q_2 \\ 1 - \dfrac{a_{ij} - q_2}{\max(q_1 - \min(a_{ij}), \max(a_{ij}) - q_2)}, & a_{ij} > q_2 \end{cases} \quad (13)$$

[051] In the above formulas, $a_{\max,j}$ and $a_{\min,j}$ respectively represent a maximum value and a minimum value of a j^{th} index, a_{ij} represents an j^{th} index in a scheme i, b_{ij} represents a normalized form of the j^{th} index in the scheme i, and q_1、q_2 represent boundary values of an interval in which an intermediate index is located.

$$Y = (y_{ij})_{m\times n} = (k_j c_{ij})_{m\times n} \quad (14)$$

[052] In the above formula, $(y_{ij})_{m\times n}$ represents a weighted normalized decision matrix, $(c_{ij})_{m\times n}$ represents an original decision matrix, and $(k_j)_{m\times n}$ represents a comprehensive weight matrix of an original compressive index.

[053] 2) Determining positive and negative ideal solutions

[054] The positive and negative ideal solutions y^+ and y^- are determined based on the weighted normalized matrix. Reference values of the positive and negative ideal solutions are selected according to the following formula:

$$\begin{cases} y^+ = \max_j y_{ij} \\ y^- = \min_j y_{ij} \end{cases} \quad (15)$$

[055] In the above formula, y_{ij} represents an element of an i^{th} row and a j^{th} column in the decision matrix, y^+ represents a maximum element value in the decision matrix, and y^- represents a minimum element value in the decision matrix.

[056] 3) Calculating nearness degrees between the evaluation scheme and the positive and negative ideal solutions

[057] The Euclidean distance, the gray correlation degree, the group utility value, and the individual deviation value are calculated to measure nearness degrees between each scheme and the positive and negative ideal solutions, and each scheme is prioritized based on the nearness degrees.

[058] The Euclidean distance is used to calculate a distance between each scheme and the ideal solution.

$$\begin{cases} D_i^+ = (\sum_{j=1}^{n} (y_{ij} - y_j^+)^2)^{\frac{1}{2}} \\ D_i^- = (\sum_{j=1}^{n} (y_{ij} - y_j^-)^2)^{\frac{1}{2}} \end{cases} \quad (16)$$

[059] In the above formula, D_i^+ represents a Euclidean distance between an i^{th} estimated value and the positive ideal solution y^+, and D_i^- represents a Euclidean distance between the i^{th} estimated value and the negative ideal solution y^-.

[060] The gray correlation degree is used to calculate a correlation degree between each scheme and the ideal solution.

[061] A gray correlation coefficient g_{ij} is calculated as follows:

$$\begin{cases} g_{ij}^+ = \dfrac{\min_i \min_j |y_j^+ - y_{ij}| + \varepsilon \max_i \max_j |y_j^+ - y_{ij}|}{|y_j^+ - y_{ij}| + \varepsilon \max_i \max_j |y_j^+ - y_{ij}|} \\ g_{ij}^- = \dfrac{\min_i \min_j |y_j^- - y_{ij}| + \varepsilon \max_i \max_j |y_j^- - y_{ij}|}{|y_j^- - y_{ij}| + \varepsilon \max_i \max_j |y_j^- - y_{ij}|} \end{cases} \quad (17)$$

[062] In the above formulas, g_{ij}^{+} represents a positive gray correlation coefficient, g_{ij}^{-} represents a negative gray correlation coefficient, and ε represents a distinguishing coefficient.

[063] The gray correlation degree is calculated as follows:

$$\begin{cases} G_i^+ = \frac{1}{n}\sum_{j=1}^{n} g_{ij}^+ \\ G_i^- = \frac{1}{n}\sum_{j=1}^{n} g_{ij}^- \end{cases} \quad (18)$$

[064] In the above formulas, G_i^+ represents a positive gray correlation degree, G_i^- represents a negative gray correlation degree, and n represents a quantity of gray correlation coefficients.

[065] The group utility value S_i is used to calculate a proximity between each scheme and the scheme closest to the positive ideal solution.

$$S_i = \sum_{j=1}^{n} \frac{y_j^+ - y_{ij}}{y_j^+ - y_j^-} \quad (19)$$

[066] The individual deviation value B_i is used to calculate a deviation degree between the worst index in each scheme and an ideal index.

$$B_i = \max_j \frac{y_j^+ - y_{ij}}{y_j^+ - y_j^-} \quad (20)$$

[067] (4) Determine a comprehensive evaluation index.

[068] In terms of a distance and a similarity, the Euclidean distance and the gray correlation degree can be integrated. Firstly, positive and negative Euclidean distances each are integrated with the gray correlation degree based on the user's evaluation preference to obtain a positive ideal distance R_i^+ and a negative ideal distance R_i^-. The positive ideal distance and the negative ideal distance are calculated according to the following formulas (21) and (22) respectively:

$$R_i^+ = \alpha D_i^- + \beta G_i^+ \quad (21)$$

$$R_i^- = \alpha D_i^+ + \beta G_i^- \quad (22)$$

[069] In the above formulas, α and β are preference coefficients used by the user to perform evaluation.

[070] In the positive ideal distance R_i^+, a longer Euclidean distance from the negative ideal solution and a higher correlation degree with the positive ideal solution, namely, a greater R_i^+, leads to a higher similarity between a to-be-evaluated scheme and the positive ideal solution. On the contrary, a longer negative ideal distance R_i^- (including a Euclidean distance from the positive ideal solution and a correlation degree with the negative ideal solution) leads to a higher similarity between the to-be-evaluated scheme and the negative ideal solution and a poorer hosting capacity of the distribution network in this scheme. The positive and negative ideal distances are integrated to obtain a relative distance R_i between each scheme and the ideal solution according to the following formula (23):

$$R_i = \frac{R_i^+}{R_i^+ + R_i^-} \quad (23)$$

[071] In terms of the nearness degree and the individual deviation value, the group utility value and the individual deviation value may be integrated to obtain their compromise coefficient Q_i, and the hosting capacity is measured according to the compromise coefficient and the following formula (24):

$$Q_i = v\frac{S_i - \min\limits_{1\le i\le n} S_i}{\max\limits_{1\le i\le n} S_i - \min\limits_{1\le i\le n} S_i} + (1-v)\frac{R_i - \min\limits_{1\le i\le n} R_i}{\max\limits_{1\le i\le n} R_i - \min\limits_{1\le i\le n} R_i} \quad (24)$$

[072] In the above formula, R_i represents an ideal distance, S_i represents the group utility value, and v represents a weight proportion of the group utility value.

[073] The compromise coefficient not only reflects a nearness degree between a scheme and an ideal scheme, but also reflects a deviation degree between a worst individual index and a project establishment index. A smaller compromise coefficient leads to a higher nearness degree between the scheme and the ideal scheme, a smaller individual deviation degree, and a higher hosting capacity of the distribution network in the scheme.

[074] (5) Perform instance analysis.

[075] Charging loads of urban electric vehicles in a corresponding spatio-temporal area are calculated based on the trip chain theory and Monte Carlo simulation, to obtain a charging load curve of each area under a hybrid chain, as shown in FIG. 3. The present disclosure adopts an IEEE33-compliant node distribution network system for simulation (a topology is shown in FIG. 4). Reference power of the distribution network is set to 10 MVA, a reference voltage at a head end of the network is set to 12.66 kV, and total load of the network is set to 3715+j2300 kVA.

[076] In this specification, the following four evaluation schemes are provided based on a quantity of connected electric vehicles and different connection manners:

[077] In scheme 1, 5000 vehicles are connected to all nodes based on a conventional load proportion.

[078] In scheme 2, all 5000 vehicles are connected to a single node in a form of a charging station (connected to node 2 near a power point in this specification).

[079] In scheme 3, 5000 vehicles are connected to a plurality of tail-end nodes of the distribution network in each functional area in a form of a charging station in proportion (namely, nodes 22, 18, 32, and 25 in this specification).

[080] In scheme 4, 5000 vehicles are connected to a plurality of head-end nodes of the distribution network in each functional area in a form of a charging station in proportion (namely, nodes 19, 7, 26, and 23 in this specification).

[081] At present, charging areas of electric vehicles are scattered and an influence of the charging load of the electric vehicle on the overall distribution network is not significant. Therefore, in instance analysis, this specification evaluates schemes of connecting electric vehicles of different scales to all nodes, some nodes, and a single node, selects an IEEE33-compliant node distribution network, and calculates a power flow considering the charging load, to obtain node voltage levels of the charging load of the electric vehicle in different connection schemes, as shown in FIG. 5. Then, a fit degree between each index and an ideal point in each scheme is calculated from technical rationality, safety and reliability, and economical efficiency, and the scheme is sorted based on an evaluation result.

[082] Based on the four schemes provided in this specification, each index is calculated based on the above constructed hosting capacity evaluation index system, as shown in Table 1.

[083] Table 1 Initial values of hosting capacity evaluation indexes of the distribution network in 4 schemes connected in a charging load

Evaluation index	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Voltage level qualification ratio T_1 /%	0.363	1	0.575	0.909
Reactive power configuration unqualification ratio T_2 /%	0	0.303	0.181	0.181
Safe operation status S_1 of the single circuit line	0.062	0.031	0	0

Short-term load ratio S_2 /kW	0.268	0.050	0.138	0.147
Network loss E_1 /kW	1085.0	247.942	485.909	307.617
Reactive power compensation cost E_2 /10,000 yuan	0	28.762	0.883	19.652

[084] An original index matrix X is constituted by the initial data in Table 1.

$$X = \begin{bmatrix} 0.363 & 0 & 0.062 & 0.268 & 1085.031 & 0 \\ 1 & 0.303 & 0.031 & 0.049 & 247.942 & 28.762 \\ 0.575 & 0.181 & 0 & 0.138 & 485.909 & 0.883 \\ 0.909 & 0.181 & 0 & 0.147 & 307.617 & 19.652 \end{bmatrix}$$

[085] Indexes in the original index matrix X are normalized, and a specific result is shown in Table 2.

[086] Calculated objective and comprehensive weights are shown in Table 3 and Table 4.

[087] Table 2 Normalized indexes obtained in different schemes

Evaluation index	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Voltage level qualification ratio T_1	0	1	0.3333	0.8571
Reactive power configuration unqualification ratio T_2	1	0	0.4000	0.4000
Safe operation status S_1 of the single circuit line	0	0.5000	1	1
Short-term load ratio S_2	1	0	0.4066	0.4476
Network loss E_1 /kW	0	1	0.7157	0.9287
Reactive power compensation cost E_2	1	0	0.9693	0.3167

[088] Table 3 Objective weights

Index type	T_1	T_2	S_1	S_2	E_1	E_2
Objective weight	0.1674	0.1655	0.1673	0.1653	0.1660	0.1687

[089] Table 4 Comprehensive weights

Index type	T_1	T_2	S_1	S_2	E_1	E_2
Comprehensive weight	0.3341	0.1101	0.1944	0.1921	0.1264	0.0428

[090] A weighted normalized matrix is obtained through matrix normalization and weight determining:

$$Y = \begin{bmatrix} 0 & 0.1101 & 0 & 0.1921 & 0 & 0.0428 \\ 0.3341 & 0 & 0.0972 & 0 & 0.1264 & 0 \\ 0.1114 & 0.0440 & 0.1944 & 0.0781 & 0.0905 & 0.0415 \\ 0.2864 & 0.0440 & 0.1944 & 0.0860 & 0.1174 & 0.0136 \end{bmatrix}$$

[091] Positive and negative ideal solutions in each scheme are as follows:

$$Y^{+} = (1,1,1,1,1,1) \quad (25)$$

$$Y^{-} = (0,0,0,0,0,0) \quad (26)$$

[092] Based on the above research content, weighted Euclidean distances, gray correlation degrees, group utility values, and individual deviation values between different indexes and the positive and negative ideal solutions in each scheme are calculated according to the above formulas, and a nearness degree between each index in each scheme and a corresponding ideal index is measured from different points of view. Calculation results are shown in Table 5.

[093] Table 5 Evaluated distance between each index in each scheme and a corresponding ideal index

Metric	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Positive ideal Euclidean distance D_i^{+}	1	0.775	0.637	0.438
Negative ideal Euclidean distance D_i^{-}	0.752	0.914	0.795	1
Positive ideal gray correlation G_i^{+}	0.998	0.873	0.978	1
Negative ideal gray correlation G_i^{-}	0.960	1	0.670	0.659
Group utility value S_i	0.654	0.442	0.440	0.258
Individual deviation value R_i	0.334	0.192	0.222	0.106

[094] From the above six metrics, the Euclidean distance is used to measure a distance between each scheme and the ideal solution. A smaller D_i^+ leads to a shorter Euclidean distance from the positive ideal solution, and a larger D_i^- leads to a longer Euclidean distance from the negative ideal solution and a better hosting capacity of the distribution network. The gray correlation degree is used to measure similarities between different schemes and the ideal scheme. A larger G_i^+ leads to a higher similarity between a scheme and the ideal scheme, and a smaller G_i^- leads to a lower similarity between the scheme and the negative ideal solution and a better hosting capacity in the scheme. The group utility value is used to quantify overall nearness degrees between different schemes and a positive ideal scheme. A smaller S_i leads to a higher nearness degree between a scheme and the ideal scheme and a better hosting degree. The individual deviation value is used to measure a deviation between an individual index in a scheme and an optimal index. A smaller R_i leads to a smaller deviation between the worst index in each scheme and the ideal index and a better hosting capacity of the distribution network.

[095] Based on the above analysis and metric settlement results in Table 6, different schemes are sorted based on individual indexes.

[096] Table 6 Sorting the schemes based on different index values

	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Positive ideal Euclidean distances D_i^+	4	3	2	1
Negative ideal Euclidean distances D_i^-	4	2	3	1
Positive ideal gray correlation degree G_i^+	2	4	3	1
Negative ideal gray correlation degree G_i^-	3	4	2	1
Group utility value S_i	4	3	2	1
Individual deviation value R_i	4	3	2	1

[097] In addition to calculating relative distances between each index in each scheme and the positive and negative ideal solutions, the compromise coefficient of the nearness degree and the individual deviation value is also considered. Results are shown in Table 7.

[098] Table 7 Comprehensive nearness coefficient and comprehensive evaluation coefficient between each index in each scheme and a corresponding ideal index

	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Comprehensive nearness coefficient R_i	0.4719	0.5018	0.5758	0.6457
Comprehensive evaluation coefficient Q_i	1	0.4206	0.4849	0

[099] Calculation results of the above two comprehensive indexes show that the hosting capacity of the distribution network in scheme 4 (connecting the electric vehicles to the plurality of tail-end nodes of the distribution network in each functional area in the form of the charging station in proportion) is the best from a perspective of the relative distance or the nearness degree of the deviation value.

[0100] The above implementations are merely described as examples, and are not intended to limit the application scope of the present disclosure. These implementations can also be implemented in various other ways, and various assumptions and substitutions can be made without departing from the technical thought of the present disclosure.

[0101] The reference to any prior art in this specification is not, and should not be taken as, an acknowledgement or any form of suggestion that such prior art forms part of the common general knowledge.

[0102] It will be understood that the terms “comprise” and “include” and any of their derivatives (e.g. comprises, comprising, includes, including) as used in this specification, and the claims that follow, is to be taken to be inclusive of features to which the term refers, and is not meant to exclude the presence of any additional features unless otherwise stated or implied.

CLAIMS:

1. A method for evaluating a hosting capacity of an urban distribution network for an electric vehicle, comprising the following steps:

performing charging load modeling for the electric vehicle based on a trip chain and a Monte Carlo method;

establishing a scheme for evaluating the hosting capacity of the urban distribution network for the electric vehicle;

normalizing an index matrix of the evaluation scheme; measuring a proximity to an ideal value by using a Euclidean distance, and performing comprehensive evaluation based on a gray correlation degree describing a degree of closeness between evaluated objects, a group utility value measuring an overall nearness degree between each scheme and an ideal solution, and an individual deviation value describing a deviation degree of a worst index in each scheme; and prioritizing the hosting capacity in the scheme based on a comprehensive evaluation standard;

determining an optimal scheme according to a result of the prioritizing;

wherein the step of performing charging load modeling for the electric vehicle based on the trip chain and the Monte Carlo method comprises:

establishing a model for the trip chain;

wherein start points and end points of the trip chain are represented by H, W, C, R, and O respectively; t_0 represents start time of the trip, $t^{\mathrm{d}}_{s_i \to d_i}$ represents driving time of a user from a start point s_i to an end point d_i, $t^{\mathrm{p}}_{d_i}$ represents dwell time at a destination d_i, and $s^{\mathrm{d}}_{s_i \to d_i}$ represents a driving distance of an i th trip; G_{TC} represents a spatio-temporal trip characteristic quantity set of the electric vehicle, which may be described as the following formula (1):

$$G_{\mathrm{TC}} = \{s_i, d_i, t_0, t^{\mathrm{d}}_{s_i \to d_i}, t^{\mathrm{p}}_{d_i}, s^{\mathrm{d}}_{s_i \to d_i}\} \quad (1)$$

$$i \in \{1,2,3,4,5\}; s_i, d_i \in \{\mathrm{H,W,C,R,O}\};$$

simplifying battery power consumption of the electric vehicle;

wherein the battery power consumption of the electric vehicle in a driving process and a battery capacity when the vehicle reaches the destination can be determined according to the following formulas (2) to (4):

$$\Delta E_{s_i \to d_i} = s^{\mathrm{d}}_{s_i \to d_i} \cdot e_0 \quad (2)$$

$$E_{d_i} = E_{d_{i-1}} - \Delta E_{s_i \to d_i} \quad (3)$$

$$\mathrm{SOC}_{d_i} = (E_{d_{i-1}} - \Delta E_{s_i \to d_i}) / B_{\mathrm{ev}} \quad (4);$$

where e_0 represents power consumption of the electric vehicle in a unit mileage, $\Delta E_{s_i \to d_i}$ represents total power consumption of the vehicle driving from s_i to s_i, B_{ev} represents a battery capacity of the vehicle, E_{d_i} represents a remaining battery capacity of the electric vehicle when the electric vehicle reaches the destination *i*, and SOC_{d_i} represents a state of charge (SOC) of the electric vehicle when the electric vehicle reaches the destination *i*;

using the Monte Carlo method to establish a model for all electric vehicles in a target area, adopting different charging decisions for users with different charging demands, and taking statistics on charging time and charging loads of the users, to obtain a total spatio-temporal charging demand distribution;

wherein the step of establishing the scheme for evaluating the hosting capacity of the urban distribution network for the electric vehicle comprises:

evaluating the hosting capacity of the distribution network when the charging load is connected in different manners based on a technique for order preference by similarity to an ideal solution (TOPSIS), and selecting six evaluation indexes:

1) ratio T_1 that a voltage offset does not exceed a threshold;

the ratio T_1 that the voltage offset does not exceed the threshold is a ratio of a quantity of nodes whose voltages do not exceed the threshold in the distribution network to a total quantity of nodes after the charging load of the electric vehicle is connected to the distribution network; the ratio T_1 is used to evaluate whether a voltage offset of each node meets a relevant technical standard after the charging load of the electric vehicle is connected;

$$T_1 = \frac{N_v}{N} \times 100\% \quad (5);$$

where N_v and N respectively represent a quantity of nodes meeting a voltage offset standard in the distribution network and a total quantity of system nodes;

2) ratio T_2 that reactive power of a node fails to reach a standard;

the ratio T_2 that the reactive power of the node fails to reach the standard is a ratio of the quantity of nodes whose power factors cannot meet a required reactive power configuration standard to the total quantity of nodes after the charging load of the electric vehicle is connected to the distribution network; the ratio T_2 is used to evaluate whether reactive power of each node meets the standard after the charging load of the electric vehicle is connected;

$$T_2 = (1 - \frac{N_q}{N}) \times 100\% \quad (6);$$

where N_q and N respectively represent a quantity of nodes meeting a reactive power standard in the distribution network and the total quantity of nodes;

3) safe network operation index S_1;

the safe network operation index S_1 indicates a ratio of a quantity of lines whose current values exceed safe carrying capacities of these lines to a total quantity of lines after the charging load of the electric vehicle is connected to the distribution network; the index S_1 is used to evaluate whether a single circuit line in the network meets a safe operation standard after the

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charging load is connected;

$$S_1 = \frac{L_{out}}{L} \times 100\% \quad (7);$$

where L_{out} and L respectively represent a quantity of lines whose currents exceed a maximum current range for safe operation in the distribution network and the total quantity of lines;

4) load ratio S_2;

the load ratio S_2 is a ratio of short-term average load of a distribution transformer or line to maximum load after the charging load of the electric vehicle is connected to the distribution network; the load ratio S_2 is used to evaluate a short-term influence on safe operation of the distribution network after the charging load is connected;

$$S_2 = \frac{P_{av}}{P_{\max}} \times 100\% \quad (8);$$

where P_{av} and $P_{\max}$ respectively represent the short-term average load and the generated maximum load in the distribution network;

5) Network loss value E_1;

the network loss value E_1 is a sum of an active power loss of each line after the charging load of the electric vehicle is connected to the distribution network; the index E_1 is used to evaluate an economical influence on operation of the distribution network after the charging load is connected;

$$E_1 = \sum (P_i^2 + Q_i^2) \cdot \frac{R_i}{U_i^2} \quad (9);$$

where P_i and Q_i respectively represent active power and reactive power of a line i, R_i represents resistance of the line i and its connected device, and U_i represents a voltage of the line i;

6) Additional reactive power cost E_2;

the additional reactive power cost E_2 is an additional cost incurred by reactive power compensation performed to ensure that a power factor is relatively reasonable after the charging load of the electric vehicle is connected to the distribution network;

$$E_2 = \eta \cdot Q_{need} \quad (10);$$

where η represents a necessary investment for reactive power compensation per unit capacity, Q_{need} represents a required reactive power compensation capacity after the charging load of the electric vehicle is connected;

wherein the step of normalizing the index matrix of the evaluation scheme; measuring the proximity to the ideal value by using the Euclidean distance, and performing the comprehensive evaluation based on the gray correlation degree describing the degree of closeness between the evaluated objects, the group utility value measuring the overall nearness degree between each scheme and the ideal solution, and the individual deviation value describing the deviation degree of the worst index in each scheme; and prioritizing the hosting capacity in the scheme based on the comprehensive evaluation standard comprises:

normalizing a decision matrix X according to the following formulas (11) to (13), and multiplying a comprehensive weight of the above indexes with the normalized decision matrix to obtain a weighted normalized matrix Y;

$$b_{ij} = \frac{a_{\max,j} - a_{ij}}{a_{\max,j} - a_{\min,j}} \quad (11)$$

$$b_{ij} = \frac{a_{ij} - a_{\min,j}}{a_{\max,j} - a_{\min,j}} \quad (12)$$

$$b_{ij} = \begin{cases} 1 - \dfrac{q_1 - a_{ij}}{\max(q_1 - \min\left(a_{ij}\right), \max\left(a_{ij}\right) - q_2)}, a_{ij} < q_1 \\ 1 \qquad , q_1 < a_{ij} < q_2 \\ 1 - \dfrac{a_{ij} - q_2}{\max(q_1 - \min\left(a_{ij}\right), \max\left(a_{ij}\right) - q_2)}, a_{ij} > q_2 \end{cases} \quad (13);$$

where $a_{\max,j}$ and $a_{\min,j}$ respectively represent a maximum value and a minimum value of a j th index, a_{ij} represents an j th index in a scheme i, b_{ij} represents a normalized form of the j th index in the scheme i, and q_1、q_2 represent boundary values of an interval in which an intermediate index is located;

$$Y = (y_{ij})_{m\times n} = (k_j c_{ij})_{m\times n} \quad (14);$$

where $(y_{ij})_{m\times n}$ represents a weighted normalized decision matrix, $(c_{ij})_{m\times n}$ represents an original decision matrix, and $(k_j)_{m\times n}$ represents a comprehensive weight matrix of an original compressive index;

determining positive and negative ideal solutions y^+ and y^- based on the weighted normalized matrix; wherein reference values of the positive and negative ideal solutions are selected according to the following formula:

$$\begin{cases} y^+ = \max\limits_j y_{ij} \\ y^- = \min\limits_j y_{ij} \end{cases} \quad (15);$$

where y_{ij} represents an element of an i^{th} row and a j^{th} column in the decision matrix, y^+ represents a maximum element value in the decision matrix, and y^- represents a minimum element value in the decision matrix;

calculating nearness degrees between the evaluation scheme and the positive and negative ideal solutions;

wherein the Euclidean distance, the gray correlation degree, the group utility value, and the individual deviation value are calculated to measure the nearness degrees between each scheme and the positive and negative ideal solutions, and each scheme is prioritized based on the nearness degrees;

the Euclidean distance is used to calculate a distance between each scheme and the ideal solutions;

$$\begin{cases} D_i^+ = (\sum_{j=1}^{n} (y_{ij} - y_j^+)^2)^{\frac{1}{2}} \\ D_i^- = (\sum_{j=1}^{n} (y_{ij} - y_j^-)^2)^{\frac{1}{2}} \end{cases} \quad (16);$$

where D_i^+ represents a Euclidean distance between an i^{th} estimated value and the positive ideal solution y^+, and D_i^- represents a Euclidean distance between the i^{th} estimated value and the negative ideal solution y^-;

the gray correlation degree is used to calculate a correlation degree between each scheme and the ideal solutions;

a gray correlation coefficient g_{ij} is calculated as follows:

$$\begin{cases} g_{ij}^+ = \dfrac{\min\limits_i \min\limits_j |y_j^+ - y_{ij}| + \varepsilon \max\limits_i \max\limits_j |y_j^+ - y_{ij}|}{|y_j^+ - y_{ij}| + \varepsilon \max\limits_i \max\limits_j |y_j^+ - y_{ij}|} \\ g_{ij}^- = \dfrac{\min\limits_i \min\limits_j |y_j^- - y_{ij}| + \varepsilon \max\limits_i \max\limits_j |y_j^- - y_{ij}|}{|y_j^- - y_{ij}| + \varepsilon \max\limits_i \max\limits_j |y_j^- - y_{ij}|} \end{cases} \quad (17);$$

where g_{ij}^+ represents a positive gray correlation coefficient, g_{ij}^- represents a negative gray correlation coefficient, and ε represents a distinguishing coefficient;

the gray correlation degree is calculated as follows:

$$\begin{cases} G_i^+ = \frac{1}{n} \sum_{j=1}^{n} g_{ij}^+ \\ G_i^- = \frac{1}{n} \sum_{j=1}^{n} g_{ij}^- \end{cases} \quad (18);$$

where G_i^+ represents a positive gray correlation degree, G_i^- represents a negative gray correlation degree, and n represents a quantity of gray correlation coefficients;

the group utility value S_i is used to calculate a proximity between each scheme and the scheme closest to the positive ideal solution;

$$S_i = \sum_{j=1}^{n} \frac{y_j^+ - y_{ij}}{y_j^+ - y_j^-} \quad (19);$$

the individual deviation value B_i is used to calculate the deviation degree between the worst index in each scheme and an ideal index;

$$B_i = \max_j \frac{y_j^+ - y_{ij}}{y_j^+ - y_j^-} \quad (20)$$

wherein the step of determining the optimal scheme according to the result of the prioritizing comprises:

integrating the Euclidean distance and the gray correlation degree in terms of a distance and a similarity; wherein positive and negative Euclidean distances each are integrated with the gray correlation degree based on the user's evaluation preference to obtain a positive ideal distance R_i^+ and a negative ideal distance R_i^-; the positive ideal distance and the negative ideal distance are calculated according to the following formulas (21) and (22) respectively:

$$R_i^+ = \alpha D_i^- + \beta G_i^+ \quad (21)$$

$$R_i^- = \alpha D_i^+ + \beta G_i^- \quad (22);$$

where α and β are preference coefficients used by the user to perform evaluation;

wherein in the positive ideal distance R_i^+, a longer Euclidean distance from the negative ideal solution and a higher correlation degree with the positive ideal solution, namely, a greater R_i^+, leads to a higher similarity between a to-be-evaluated scheme and the positive ideal solution; a longer negative ideal distance R_i^- leads to a higher similarity between the to-be-evaluated scheme and the negative ideal solution, and a poorer hosting capacity of the distribution network in the scheme; the positive and negative ideal distances are integrated to obtain a relative distance R_i between each scheme and the ideal solutions according to the following formula (23):

$$R_i = \frac{R_i^+}{R_i^+ + R_i^-} \quad (23);$$

integrating the group utility value and the individual deviation value to obtain their compromise coefficient Q_i in terms of the nearness degree and the individual deviation value, and measuring the hosting capacity according to the compromise coefficient and the following formula (24):

$$Q_i = v\frac{S_i - \min\limits_{1\le i\le n} S_i}{\max\limits_{1\le i\le n} S_i - \min\limits_{1\le i\le n} S_i} + (1-v)\frac{R_i - \min\limits_{1\le i\le n} R_i}{\max\limits_{1\le i\le n} R_i - \min\limits_{1\le i\le n} R_i} \quad (24);$$

where R_i represents an ideal distance, S_i represents the group utility value, and v represents a weight proportion of the group utility value;

wherein the compromise coefficient not only reflects the nearness degree between a scheme and an ideal scheme, but also reflects a deviation degree between a worst individual index and a project establishment index; a smaller compromise coefficient leads to a higher nearness degree between the scheme and the ideal scheme, a smaller individual deviation degree, and a higher hosting capacity of the distribution network in the scheme.

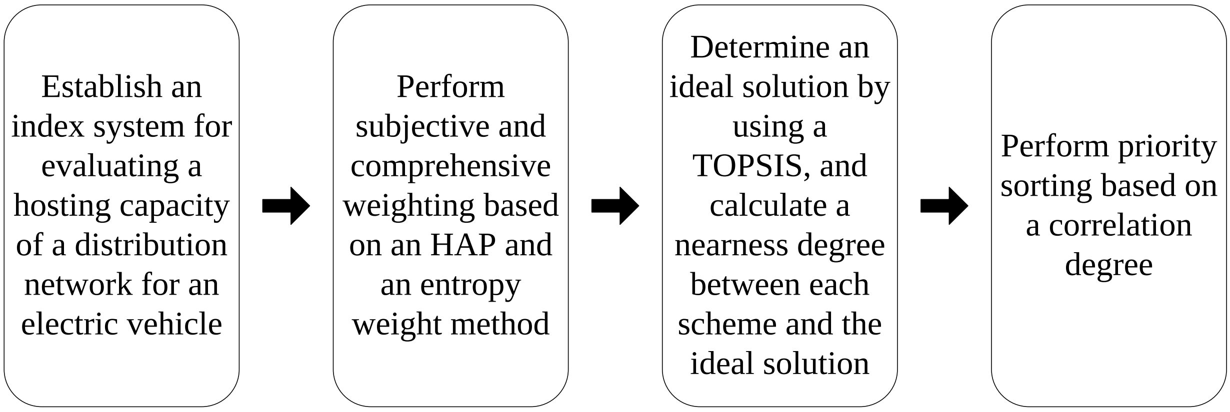

Establish an index system for evaluating a hosting capacity of a distribution network for an electric vehicle
Perform subjective and comprehensive weighting based on an HAP and an entropy weight method
Determine an ideal solution by using a TOPSIS, and calculate a nearness degree between each scheme and the ideal solution
Perform priority sorting based on a correlation degree

FIG. 1

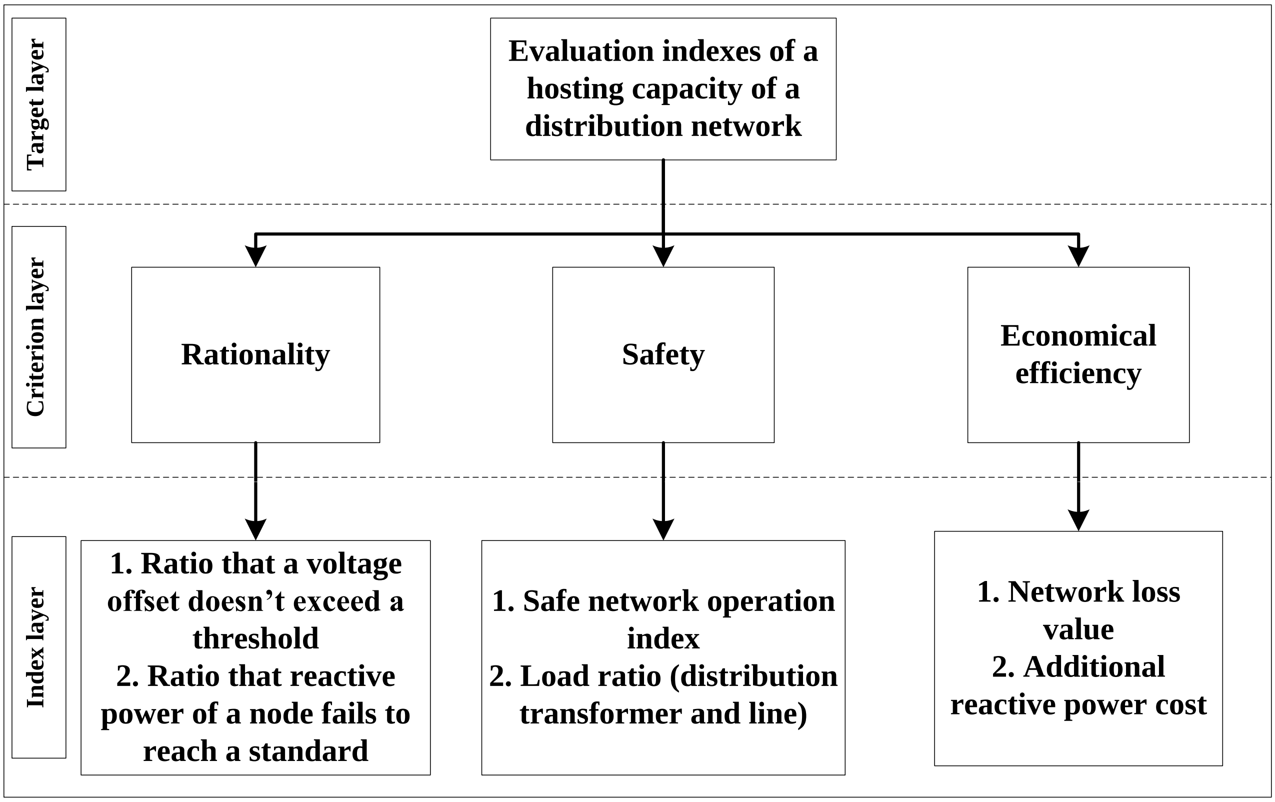
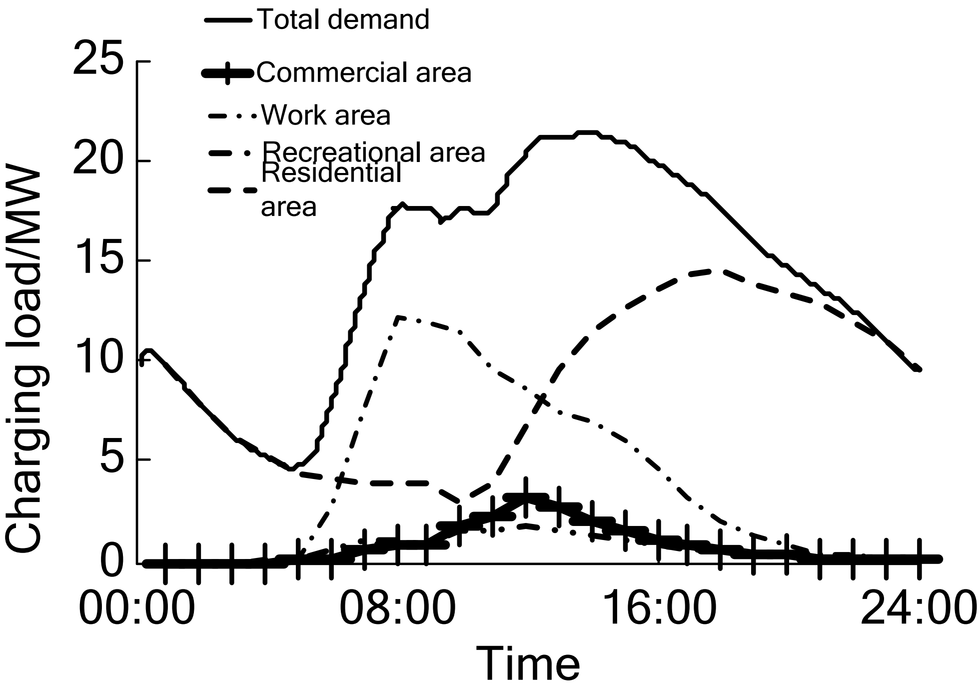
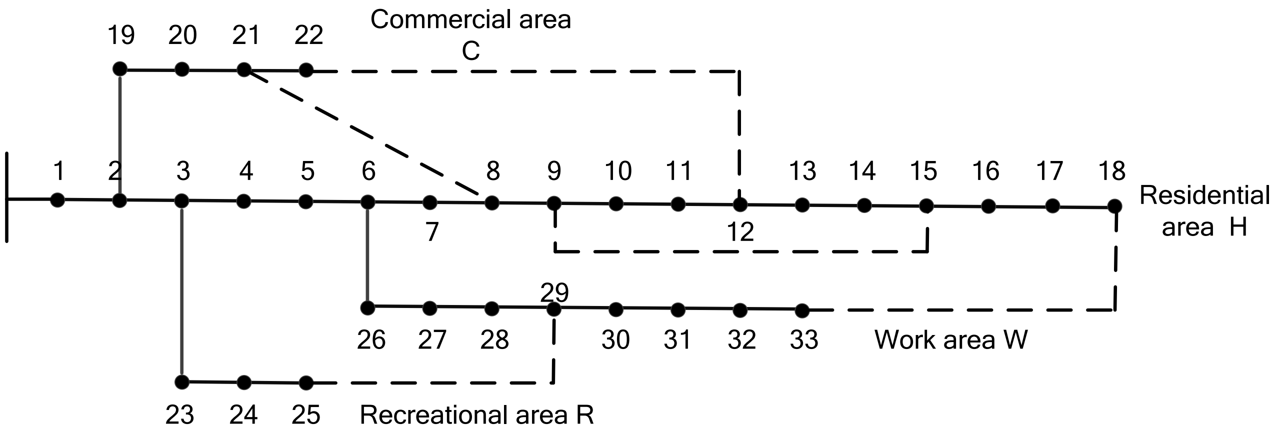

Target layer
Evaluation indexes of a hosting capacity of a distribution network
Criterion layer
Rationality
Safety
Economical efficiency
Index layer
1. Ratio that a voltage offset doesn't exceed a threshold
2. Ratio that reactive power of a node fails to reach a standard
1. Safe network operation index
2. Load ratio (distribution transformer and line)
1. Network loss value
2. Additional reactive power cost

FIG. 2



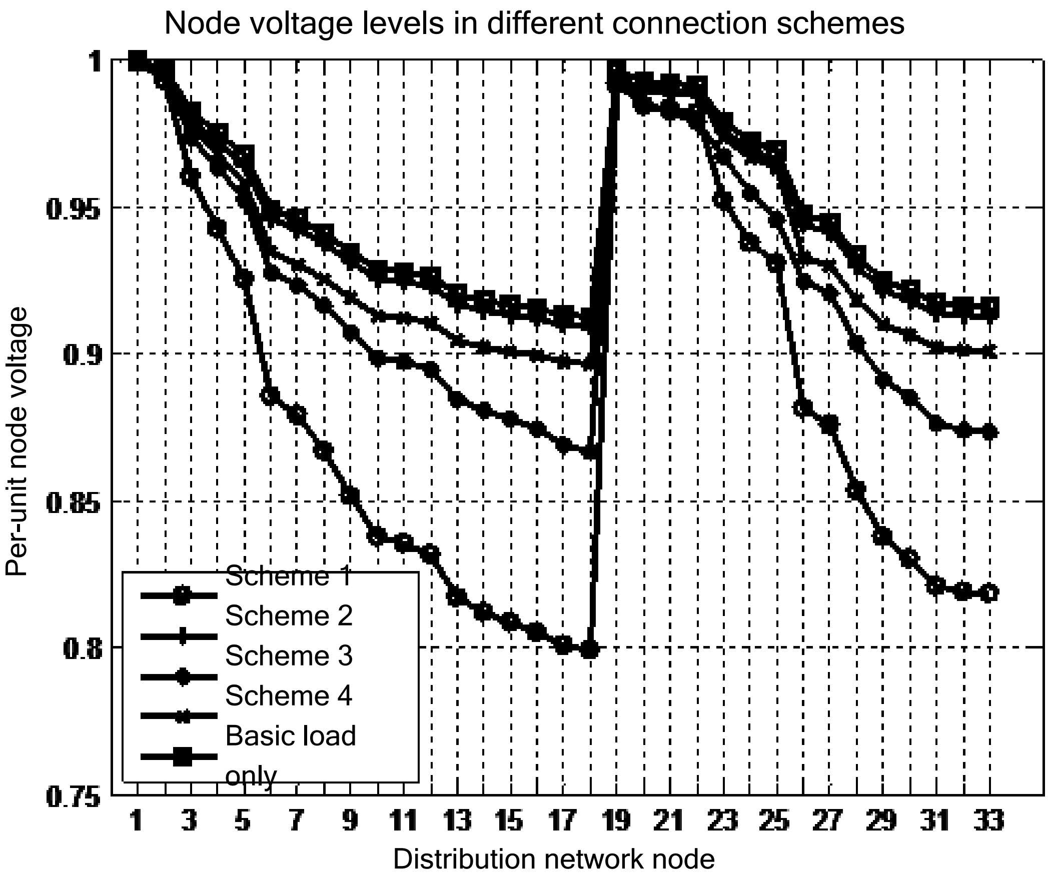
Total demand
Commercial area
Work area
Recreational area
Residential area
25
20
15
10
5
0
Charging load/MW
00:00
08:00
16:00
24:00
Time

FIG. 3



Commercial area C
19 20 21 22
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Residential area H
29
26 27 28 30 31 32 33
Work area W
23 24 25
Recreational area R

FIG. 4



Node voltage levels in different connection schemes
Per-unit node voltage
1
0.95
0.9
0.85
0.8
0.75
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
Distribution network node
Scheme 1
Scheme 2
Scheme 3
Scheme 4
Basic load only

FIG. 5