

Assessing the Impact of Advanced Technologies on Utilization Improvement of Substations

Dong Han[†], Zheng Yan^{*}, Dao-Tian Zhang^{*} and Yi-Qun Song^{*}

Abstract – The smart substation is the heart of a transmission system, which is particularly emphasized as the most significant composition of smart grids in China. In order to assess the functionality performance of substation technologies, this paper presents methods used to identify the most promising solutions for smart substation design and to evaluate the technical levels of available technologies. The multi-index optimization model is presented to address the issue of smart substation planning. A mathematical model of the planning decision problem is established with multiple objectives consisting of economic, reliability, and green key indices, and many kinds of concerns including physical and environmentally friendly operations are formulated as a set of constraints. With respect to the assessment of the technical level regarding integration of advanced technologies into a substation, a modified grey whitenization weight function is adopted to structure a novel grey clustering method. The proposed grey clustering approach is used to overcome the difficulty of insufficient quantitative assessment capacity for traditional methods. The evaluation of technical effects provides the classification definition for the development phase and the maturity level of the smart substation. The effectiveness of the proposed approaches in planning decision-making and evaluation of construction efforts is demonstrated with case studies involving the actual smart substation projects of Wenchongkou substation in China Southern Power Grid (CSG) and Mengzi substation in State Grid Corporation of China (SGCC).

Keywords: Smart substation, Intelligent technologies, Optimal designed scheme, Technical performance assessment, Evaluation methods

1. Introduction

The development of smart substations in China has led to the construction of smart transmission grids, which play an important role in demonstrating the performance effects of applied intelligent technologies and devices. Instead of a traditional substation, a smart substation enables information sharing and the interoperation of electrical equipment [1]. Besides the fact that a smart substation has the advanced features of a digital substation, more innovative technologies and equipment are brought into the integration of measurement, detection, control, and protection functionalities [2].

Although smart substations have an impact on power system automation, the uncertainties from advanced substation technologies may threaten the stability and reliability of smart devices, which then makes the determination of suitable technologies and equipment difficult for a smart substation design scheme. Hence, establishing a model for the evaluation of smart substations is not only meaningful but also critical for the planning

decision-making of the whole smart grid.

Meanwhile, it is also significant to evaluate the technical level and maturity of a built smart substation. In view of the large-scale investment, long-term construction, and uncertain outcome of a demonstration project, it is necessary for the post-analysis to assess the benefits from the pilot project, which is also beneficial for the decision maker to identify the problems faced in the construction of smart substations.

In the early days of smart substations, U.S. EPRI delivered a technical report about the preliminary assessment of smart substations [3] in which an approach was proposed to evaluate and analyze the developments in transmission substation equipment and concepts, and the current trends and further suggestions for the project were also reviewed. Recently, U.S. EPRI focused on the specific technological functionalities, such as cyber security and control-system remote-access strategies [4]. In [5], a novel whole-view approach for onsite commissioning of the secondary system in a smart substation was presented to evaluate the complexity of digitally networked information flows. A study of the construction and evaluation of a smart substation information integration scheme was reported in [6], in which the real-time performance and reliability of the proposed scheme were assessed to provide a new way of building an intelligent substation automation system.

[†] Corresponding Author: Key Laboratory of Control of Power Transmission and Conversion (Shanghai Jiao Tong University), Ministry of Education, China. (qbilial@sjtu.edu.cn)

^{*} Key Laboratory of Control of Power Transmission and Conversion (Shanghai Jiao Tong University), Ministry of Education, China.

Received: March 26, 2014; Accepted: May 4, 2015

As concluded by previous scholars, the analysis and evaluation of a smart substation is a complex matter. To analyze the impacts of available substation technologies and equipment, this paper will conduct the modeling for a design scheme and performance assessment of a smart substation project using the evaluation methods from ex post and ex anti perspectives. The proposed algorithms can help in the decision-making process for planning the substation networks and components and provide a qualitative assessment to classify the development phase of a smart substation.

The remainder of this paper is structured as follows. Section 2 presents the methodologies used to evaluate the design scheme and the technical performance. The results and more application scenarios are described in Section 3, and Section 4 concludes this paper.

2. Methodologies and Modeling

2.1 Review smart substations in china

Since 2009, when the concept of the smart grid was first presented in China, smart substations have been recognized as the most significant parts of the smart grid, which has led to a rapid increase in the number of smart substations. According to a survey from SGCC [7], there were 46 newly-built and 28 renovated smart substations in the pilot stage of smart grids. The future planning objective is that all the newly-built substations and typical substations in operation will fully meet the standards and rules of smart substations. CGS achieved the remarkable result of establishing two smart and green substations, which represent the state of the art, on Hengqin Island of Guangdong province [8].

In contrast with conventional substations, the typical features of smart substations are summarized as follows [9].

- More intelligent components and equipment are applied in reliable physical networks.
- The logical network architecture in Fig. 1 is composed of process level, bay level, and substation level.
- Information flow satisfies the attributes of real-time, reliable and efficient transmission of data.

The substation development shows a trend from conventional to digital substations and then from digital to smart substations. Simply generalized, physical and logical integrations are the major properties of the technological progress of substations [10].

2.2 Modeling planning design scheme

A multi-index optimal model is proposed to implement the planning design scheme of a smart substation. The concept of multi-index self-approximate-optimal operation

for a smart grid has been presented in [11]. In this paper, a multi-index is the index set consisting of economic, reliability, and green key indices. The objective is to minimize the costs of substation devices, to maximize the benefits from green operation and maintenance, and to increase the reliability of physical and cyber systems. The optimization problem can be formulated by the following model with the objective function, constrained network topology, and green development:

$$\begin{aligned} \min F(X, U) &= \sum_{t=1}^T \sum_{i=1}^N \omega_{it} f_i(x_t, u_t) \\ \text{s.t. } h_{it}(x_t, u_t) &= 0, \quad \forall t \in [1, T] \\ g_{it}(x_t, u_t) &\geq 0, \quad \forall t \in [1, T] \end{aligned} \quad (1)$$

where

- ω_{it} the weight of the index $f_i(\cdot)$ at the t th time slot,
- x_t state variable at the t th time slot,
- u_t network variable at the t th time slot,
- $h_t(\cdot)$ network structure constraints at the t th time slot,
- $g_t(\cdot)$ reliability and economic investment limit constraints at the t th time slot,
- T total number of planning time slots,
- N overall number of indices.

with the i th index $f_i(x_t, u_t)$ representing, respectively:

$$f_1(x_t, u_t) = \sum_{s=1}^S C_s(x_t, u_t) = (1+r)^{-t} \sum_{s=1}^S u_{ts} a_{ts} \quad (2)$$

$$f_2(x_t, u_t) = \sum_{s=1}^S B_s(x_t, u_t) = (1+r)^{-t} \sum_{s=1}^S u_{ts} m_{ts} \quad (3)$$

$$f_3(x_t, u_t) = \sum_{s=1}^S L_s(x_t, u_t) = (1+r)^{-t} \sum_{s=1}^S l_{ts} v_t \quad (4)$$

The subscript s denotes the s th device in a substation. The variable r represents the discount rate. Eqs. (2) and (3) are the investment and operation costs, where a_{ts} and m_{ts} are the investment cost and the operation and maintenance cost for the s th item of equipment at the t th time slot. In (4), $L_s(\cdot)$ is the outage loss cost of the s th device, where l_{ts} indicates the loss due to the outage of the s th device and v_t represents the loss cost at the t th time slot.

For the constraint sets, the equality constraints indicate the interconnection interface with a substation automation system, by which the current status of information flow can also be reflected. In Fig. 1, various pieces of devices are scattered over the process, bay, and substation levels. The interfaces from one item of equipment to another and from level to level form an overall network topology structure. The inequality constraints indicate a smart substation composed of a variety of advanced equipment, all of which should satisfy the green planning requirements such as efficient use of land and water and the protection of the environment. In addition, reliability and economic

investment limitations related to the equipment are also embraced in the inequality constraint sets.

In summary, an optimal planning scheme should be selected from all candidate design schemes. A comprehensive analysis including reliability and economic evaluation will support the final solution. It ensures that a reliable physical network, available logical system, real-time information flow, and economic investment and operation will be considered in the designed substation.

2.3 Evaluation of technical performance

In order to reflect the technical level and functional characteristics of the substations, it is necessary to present an evaluation method. However, for traditional comprehensive assessment methods such as the Analytic Hierarchy Process (AHP), it is difficult to explicitly give the maturity of a substation in a quantitative manner. To handle such a technical problem, the new grey cluster analysis method, which is based on the modified whitenization weight function, is developed in this paper. According to grey system theory [12], it is through the organization of raw data that development laws, if any exist, can be sorted out. In other words, this is a path of finding out realistic governing laws from the available data. Hence, for a pilot substation, a suitable grey classification law can qualitatively assess the substation technology advances in the context of data deficiency and uncertain information, both of which are frequently encountered in the initial construction phase. The proposed evaluation method as an available approach with the ability to perform quantitative and qualitative assessment is proven to solve the problem of the evaluation of the technical progress of substations through the definition of grey classes which comprise traditional, digital, and smart substations.

In theory, the concept of grey number is employed to create a range indicating the boundary of incomplete information. The whitenization weight function is used to describe the preference of a grey number for taking values in its range. For a general interval grey number $\otimes \in [\underline{a}, \bar{a}]$, $\bar{\otimes} \in [\underline{a}, \bar{a}]$, a whitenization value $\bar{\otimes}$ denotes the simulative truth information of \otimes . The k th whitenization weight function F is formulated by the following:

$$\tilde{\otimes}^{(k)} : \{\otimes^{(k)}\} \rightarrow f^{(k)} \quad (6)$$

which has a critical impact on the evaluation results for the grey cluster method.

In general, the triangular whitenization weight function in Fig. 2 is widely applied in grey system analysis. There are n grey classes, and accordingly λ^k denotes the whitenization value of the k th grey number. Supposing there is a point sequence $\{\lambda_0, \lambda_1, \lambda_2, \dots, \lambda_n, \lambda_{n+1}\}$, f_j^k is a triangular whitenization weight function for the interval $[\lambda_{k-1}, \lambda_{k+1}]$.

For the index j , in terms of grey class k , the whitenization weight function follows the piecewise linear equations given below:

$$f_j^k(x) = \begin{cases} 0 & x \notin [\lambda_{k-1}, \lambda_{k+1}] \\ \frac{x - \lambda_{k-1}}{\lambda_k - \lambda_{k-1}} & x \in (\lambda_{k-1}, \lambda_k] \\ \frac{\lambda_{k+1} - x}{\lambda_{k+1} - \lambda_k} & x \in (\lambda_k, \lambda_{k+1}] \end{cases} \quad (7)$$

The whitenization weight function has been applied widely in many fields. For the evaluation problem, there are some technical challenges for its successful application. For example, when the sample value of an upper grey class is more than the center point, the triangular whitenization weight function and the center points are negatively correlated, which is not in accordance with the reality that the greater λ^k should have the better $f^{(k)}$.

Therefore, an improved triangular whitenization weight function is presented as follows. For the upper grey class, the triangular whitenization weight function is defined and displayed in Fig. 3:

$$f_{j,upper}^k(x) = \begin{cases} 0 & x \in [-\infty, \lambda_{n-1}] \\ \frac{k(x - \lambda_{n-1})}{\lambda_n - \lambda_{n-1}} & x \in [\lambda_{n-1}, \lambda_n] \\ \frac{(1-k)x + k - \lambda_n}{1 - \lambda_n} & x \in (\lambda_n, 0] \end{cases} \quad (8)$$

Similarly, for the lower grey class, the equations can be formulated as

$$f_{j,lower}^k(x) = \begin{cases} 0 & x \in [\lambda_2, +\infty] \\ \frac{k(x - \lambda_2)}{\lambda_1 - \lambda_2} & x \in (\lambda_1, \lambda_2] \\ \frac{(k-1)x + \lambda_1}{\lambda_1} & x \in [0, \lambda_1] \end{cases} \quad (9)$$

Based on the principle that the sum of all grey classes is equal to one, the whole modified triangular whitenization weight function is shown in Fig. 4. The modified whitenization weight functions displayed in Fig. 4 not only have intrinsic advantages but can also solve specific evaluation problems. From the perspective of quantitative evaluation, the monotony of the improved functions ensures that the evaluation results truly reflect the objective law.

The evaluation procedure for a substation based on the

grey cluster analysis method is described in brief:

- Step 1.** Establish a grey class evaluation set of substations $\{I, J, K\}$, in which I denotes the substation set, J denotes the evaluation index set, and K denotes the grey class set.
- Step 2.** Calculate the evaluation indices, and perform the standardization.
- Step 3.** Select the whitenization weight functions for the standardized indices to obtain the grey classes. In this step, λ_k is often given an initial value by expert marking.
- Step 4.** A grey cluster evaluation matrix is developed. For a grey class k , the grey cluster evaluation element σ^k in the matrix can be described as follows.

$$\sigma^k = F^k \eta^k = \begin{bmatrix} f_{11}^k & f_{12}^k & \dots & f_{1m}^k \\ f_{21}^k & f_{22}^k & \dots & f_{2m}^k \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1}^k & f_{m2}^k & \dots & f_{mm}^k \end{bmatrix} \begin{bmatrix} \eta_1^k \\ \eta_2^k \\ \vdots \\ \eta_m^k \end{bmatrix} = \begin{bmatrix} \sigma_1^k \\ \sigma_2^k \\ \vdots \\ \sigma_m^k \end{bmatrix} \quad (10)$$

where η^k is the weight vector, which can be obtained by the AHP evaluation method [13].

- Step 5.** The grey cluster analysis is performed and the evaluation results can be acquired. For the i th substation, the evaluation results are given below:

$$\sigma_i = [\sigma_i^1, \sigma_i^2, \sigma_i^3] \quad (11)$$

Based on Eq. (11), the technical level of a substation can be classified. Suppose that

$$\max_{1 \leq k \leq n} \{\sigma_i^k\} = \sigma_i^{k^*} \quad (12)$$

Then the i th substation belongs to the grey class k^* . When k^* is equal to one, the technical level is defined as traditional substation; when k^* is equal to two or three, the technical level can be regarded as digital or smart substation.

3. Case Study

Two case studies have been used in this paper to analyze the proposed approaches. First, for the Wenchongkou substation in CGS, the technical and economic requirements for a smart substation have been given in the bid documents [14], and an optimal multi-objective planning design scheme is presented here. The second case study is the technical-level evaluation for substations, which includes the Mengzi smart substation and other digital and traditional substations in SGCC.

3.1 Planning scheme of the Wenchongkou substation

In the bid documents of the 110 kV Wenchongkou substation, the topology of the network shows the connection status for nodes in the process level, bay level, and substation level. At the substation level, the electronic transformers and intelligent primary equipment will be applied in the substation. The mean time between failure (MTBF) index for the cyber system is limited to the maximum level. Three candidate schemes are presented to evaluate the planning effects. The main information including the transmission mode, network structure, and equipment application is displayed in Table 1 and Figure 5.

In Table 1, the element of the equipment number set $\{L..., M..., S..., T..., Q..., F..., K...\}$ in sequence denotes the allocation number of the logical, measurement, supervision, transformer and sensor, quality of electricity, functional, and mechanical nodes in the designed substation. Moreover, the elements in Table 1 have been allocated in Fig. 5 for three candidate schemes. The networks in Schemes 1 and 2 are designed based on IEC 61850 Edition 1.0 [15] in Figs. 5(a) and 5(b), and a new standard named IEC 61850 Edition 2.0 [16] is applied to the design of Scheme 3 in Fig. 5(c). Other network nodes and their meanings are described in [17] in detail.

The proposed optimization model in Eq. (1) is a nonlinear and mixed-integer programming problem in mathematics. In order to implement the ex-post evaluation for the substation, a classical heuristics optimization algorithm, that is, particle swarm optimization (PSO) [18], is used to obtain the solution. Based on the main data given for the abovementioned evaluated substations, the planning results in different scenarios are shown in Tables 2 and 3. The cases in Table 2 illustrate the economic (Ec.), reliability (Re.), and comprehensive (Co.) index values in different scenarios. The Ec. index includes the investment and operation cost. The Re. index indicates the outage loss cost considering the line outage in the network structure of a substation. The Co. index result can be obtained from the sum of the weight for both index Ec. and index Re.. If the weights of the Ec. indices are higher than those of Re. indices, the optimal plan will be not reliability-oriented. As for the three planning design schemes, higher comprehensive evaluation values are obtained by Scheme 3. The best planning design for a smart substation should comply with Scheme 3. Furthermore, Scheme 3 is composed of more smart devices, redundant logical nodes, and a robust network topology structure, which indicates the development direction of smart substation.

The AHP method is used by the decision maker to address the smart substation planning problem with multiple objectives in this paper. The AHP approach has been proven to be effective in solving multi-criteria problems including planning, selecting the best among the alternatives, and allocation of resources [19]. It is helpful for making decisions where conflicting evaluation criteria

exist. Thus, the AHP method is used as the decision-making technique for the proposed approach because of its efficiency in coping with quantitative and qualitative criteria for the resolution of the problem. The steps of the AHP algorithm are described briefly as follows.

- 1) The hierarchical model of the metrics for the attributes is structured.
- 2) The judgment matrix is set up. The elements in the judgment matrix represent the decision-maker's knowledge about the relative importance of any pair of attributes. An intensity scale of importance is used to show how to transform the linguistic terms into numerical intensity values [20].
- 3) The maximum eigenvalue and its corresponding eigenvector of the judgment matrix can be calculated. Moreover, the weight vector including weight values for all attributes is equal to the normalized eigenvector.
- 4) The index of consistency ratio (CR) [21] is used to check the effectiveness of the established judgment matrix.

The AHP method is implemented to obtain the following judgment matrix of indices:

$$J = \begin{bmatrix} 1 & 1/3 & 1/5 \\ 3 & 1 & 1/3 \\ 5 & 3 & 1 \end{bmatrix} \quad (13)$$

Eq. (13) shows that f_1 is less important than f_2 , and f_3 is more significant than f_2 in the view of experts. Thus, the weights of the three objective functions are determined.

$$W = \begin{pmatrix} w_1 \\ w_2 \\ w_3 \end{pmatrix} = \begin{pmatrix} 0.10 \\ 0.21 \\ 0.64 \end{pmatrix} \quad (14)$$

The planning results obtained through the AHP method are displayed in Table 3. In the scenario, the comprehensive evaluation results are also from the weighted sum of the three indices, but the indices have been normalized. As shown in Table 3, considering that the reliability plays an important role in the intelligence property for a smart substation, the higher weight value is given to the reliability objective function. Therefore, Scheme 3 can be regarded as the best design as it has the largest comprehensive evaluation value. The comprehensive results listed in Tables 2 and 3 together demonstrate that a smart substation should have more reliability.

3.2 Performance evaluation of the substations

In this section, eight substations including the Mengzi substation (Substation F) in SGCC are evaluated based on the methodologies proposed in Section II. It is necessary

to establish an evaluation index system for a substation before the technical performance assessment is conducted. Therefore, 16 indices indicate that the functional characteristics of substation technologies are used to implement the evaluation process. They are, respectively, the ratio of smart plug and play devices, the success rate of interoperability of smart devices, the communication success rate, the network bandwidth, the rate of Ethernet coverage, the average number of daily staff, the average time of switching operations, the average maintenance cycle of devices, the yearly outage time, the yearly rate of operation accidents, the equipment failure rate, the mean time to repair, the success rate of protection operations, the area covered by the substation, the total length of cable of the secondary system, and the photovoltaic power-generation capacity. In the whole assessment procedure, the evaluation indices represent the intelligence, reliability, efficiency, and greenness, and can be calculated based on the actual data.

Table 4 gives the calculation results from the application of the proposed modified grey clustering analysis method. Figure 6 shows the evaluation results of grey clustering for the eight substations. Substations B, D, and E can be taken as traditional substations, Substation C and H are digital substations, and Substations A, F, and G have reached the technical level of smart substations. In addition, any substation can be ranked with others in accordance with their evaluation values. For example, for the digital substation set, Substation H has a higher technical level than Substation C.

Considering the advantage of the AHP method, that is, that multiple evaluated objects can be dealt with conveniently and effectively in the weight calculation procedure, the analysis results from the grey clustering analysis approach can be verified by the AHP algorithm.

In comparison with the data in Fig. 6, the results calculated by the AHP approach are displayed in Fig. 7. The sorting of the substations obtained with the AHP algorithm has the same trend as that given by the approach proposed in this paper, which indicates that neither of methods can render the paradox about the technical advance assessment of the substations. Hence, the modified grey clustering analysis method may be used to evaluate the technical performance of substations. Although AHP has been employed widely in various fields, this method can only provide comprehensive evaluation results, which means AHP, as a classic evaluation approach, is more suitable for carrying out qualitative assessment than quantitative analysis. However, the grey clustering analysis method can not only obtain qualitative results in the evaluation process to identify the sequence of technical progress of substations but also classify the maturity rating of the evaluated substations based on the quantitative results.

A further discussion about the application of the modified grey clustering analysis method in this paper is

presented. In terms of the fundamentals of the proposed abovementioned method, the whitenization weight function plays a significant role in the correction of the evaluation results. As a result, a sensitivity analysis of grey class k is performed to reflect the influence. Three substations are selected to display the change of evaluation results with different k values in Fig. 8. From the picture, the evaluation sequence of substations is not transformed with the increase in the values of k , but the diversities of the evaluation results from the selected substations will be weakened, which means the reliability of the quantitative analysis will be damaged. In other words, supposing that a higher k value is set, it will be disadvantageous to employ the modified grey clustering method in the procedure evaluating the technical progress. In the authors' opinion, the value of grey class k should be taken as a tradeoff between a quantitative and qualitative evaluation analysis. Although the reliability of the qualitative evaluation can be improved when k becomes larger, the difference in results compared to the quantitative analysis will not be seen as clearly as in the case of smaller k . Therefore, when the requirements of qualitative evaluation can be met, a choice of smaller k may be suitable and feasible.

4. Useful Hints

4.1 Figures

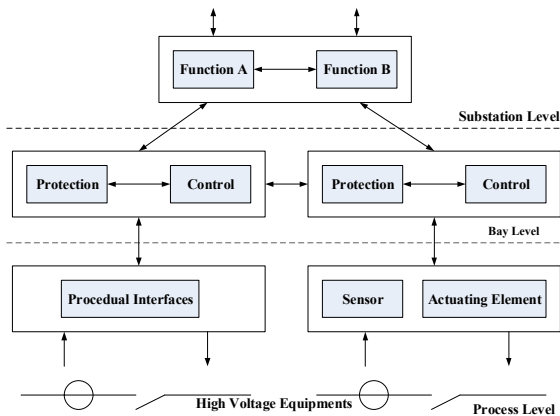


Fig. 1. Logical structure and main components for a substation

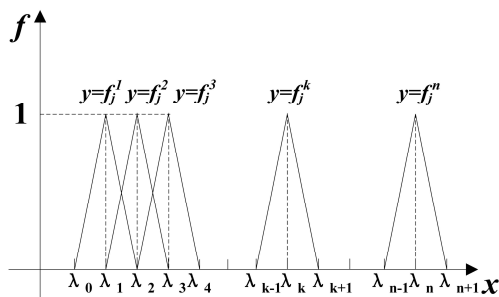


Fig. 2. Graph of triangular whitenization weight function

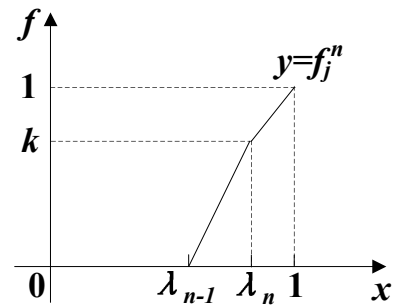


Fig. 3. Graph of improved whitenization weight function for upper grey class

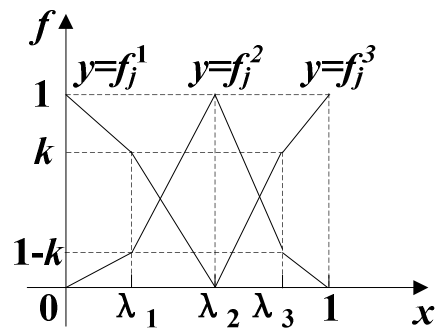


Fig. 4. Graph of improved whitenization weight functions for upper, middle and lower grey classes

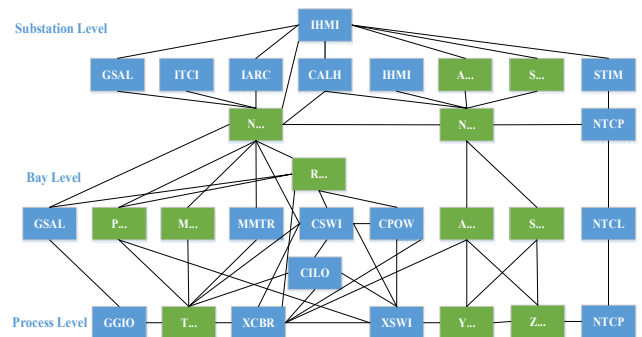


Fig. 5a. The network structure of substation in Scheme 1

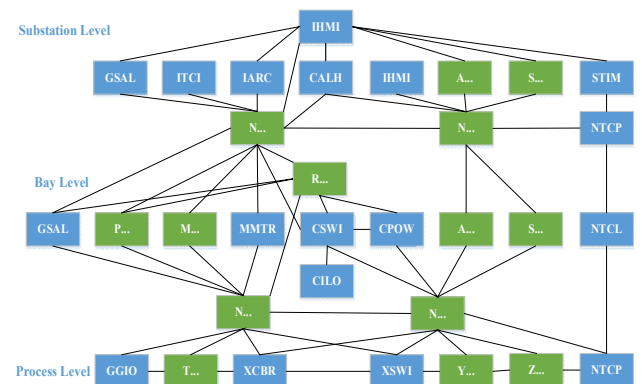


Fig. 5b. The network structure of substation in Scheme 2

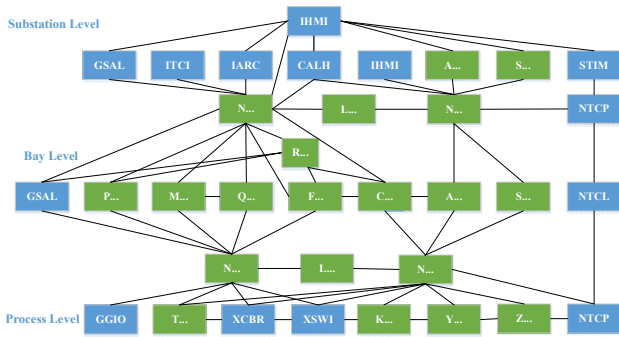


Fig. 5c. The network structure of substation in Scheme 3

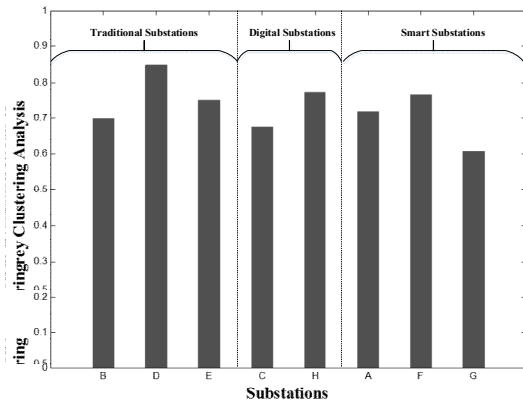


Fig. 6. The quantitative grey clustering evaluation results for eight substations

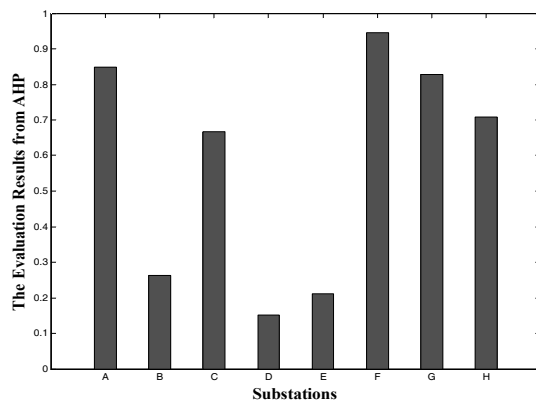


Fig. 7. The evaluation results from the application of the AHP method for eight substations

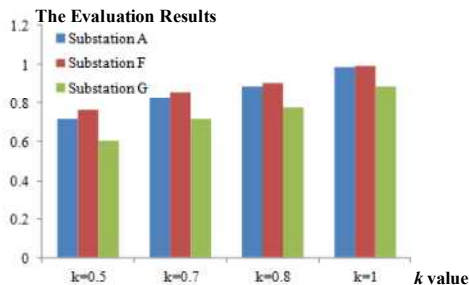


Fig. 8. The evaluation results of smart substations in different scenarios based on the change of k value

4.2 Tables

Table 1. The plan of equipment allocation in the schemes

| | Design 1 | Design 2 | Design 3 |
|------|----------|----------|----------|
| L... | 2 | 2 | 8 |
| M... | 7 | 8 | 13 |
| S... | 4 | 4 | 11 |
| T... | 3 | 5 | 20 |
| Q... | 0 | 0 | 6 |
| F... | 0 | 0 | 9 |
| K... | 0 | 0 | 5 |

Table 2. The planning results of three schemes in different weight scenarios

| | Planning design schemes | | | | | | | | |
|-------|-------------------------|-----|------|----------|-----|------|----------|-----|------|
| | Scheme 1 | | | Scheme 2 | | | Scheme 3 | | |
| | Ec. | Re. | Co. | Ec. | Re. | Co. | Ec. | Re. | Co. |
| 2:3:5 | 2.99 | 1 | 20.0 | 3.76 | 1.8 | 27.8 | 5.10 | 1.5 | 33.0 |
| 3:4:3 | 3.27 | 0.9 | 25.6 | 3.92 | 1.5 | 31.9 | 5.53 | 1.4 | 42.9 |
| 4:3:3 | 3.56 | 0.8 | 27.3 | 4.13 | 1.2 | 32.5 | 5.66 | 1.2 | 43.2 |
| 2:2:6 | 2.73 | 1.2 | 19.9 | 3.48 | 1.9 | 25.3 | 4.82 | 1.9 | 30.7 |

Table 3. The planning results of three schemes based on the AHP method

| Design schemes | Weights from AHP ($w_1:w_2:w_3$) | | | Comprehensive evaluation results |
|----------------|------------------------------------|--|--|----------------------------------|
| 1 | 0.1:0.26:0.64 | | | 0.32 |
| 2 | | | | 0.26 |
| 3 | | | | 0.67 |

Table 4. The grey clustering analysis results from eight evaluated substations

| Substation | Lower grey cl ass value | Middle grey c lass value | Upper grey cl ass value |
|------------|-------------------------|--------------------------|-------------------------|
| A | 0.0000 | 0.2822 | 0.7178 |
| B | 0.6976 | 0.2721 | 0.0303 |
| C | 0.1389 | 0.5706 | 0.2904 |
| D | 0.8457 | 0.1135 | 0.0408 |
| E | 0.7493 | 0.2157 | 0.0350 |
| F | 0.0000 | 0.2368 | 0.7632 |
| G | 0.1148 | 0.2777 | 0.6075 |
| H | 0.0393 | 0.5908 | 0.3699 |

5. Conclusion

This paper has presented methodologies for evaluating smart substations in China from the ex post and ex ante perspectives. In the ex ante evaluation process, for a smart substation, the proposed approach develops a multi-index optimization model to design the planning scheme. The assessment solution shows the tradeoff between reliability and economic cost of substation equipment. The simulation results show that a design scheme that integrates more advanced substation technologies and has redundant logical nodes and a robust network topology structure can enhance the reliability of operation, although it will have a much higher economic cost. The proposed methodology,

which is used to evaluate the plan of a substation, can provide an optimal solution for the decision-maker based on multicriteria analysis. Through the comparison of the results obtained with different weight combinations, it is illustrated that the difference of optimal solutions for the candidate schemes based on AHP can be shown more obviously than when using the given fixed weights. The reason is that the AHP method relies on the options chosen by the decision-maker when considering different attributes, and it is beneficial to provide an optimal solution with consideration of the characteristics of the attributes on which the decision-maker focuses.

As for the ex post evaluation, a modified grey clustering analysis method is proposed to assess the technical progress of a substation, by which the maturity levels of substation technologies can be determined. Novel triangular whitenization weight functions are defined to formulate the proposed evaluation approach. Through the whole of the ex post assessment procedure, the evaluated substation can be classified as a traditional, digital, or smart substation. Moreover, the sorting of the substations obtained with the proposed modified grey clustering analysis method has the same trend as that given by the AHP algorithm, which demonstrates the effectiveness and correctness of the application of the presented methodology. However, the AHP method, as a typical evaluation method, only performs the sorting of substations qualitatively. It is difficult to classify substations into corresponding categories using AHP. Hence, the proposed ex post evaluation method is a practical way to identify the technical advancement of substations.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 51377103).

References

- [1] F. X. Li, W. Qiao, H. B. Sun, H. Wan, J. H. Wang, Y. Xia, Z. Xu and P. Zhang, "Smart transmission grid: vision and framework," *IEEE Trans. Smart Grid*, vol. 1, pp. 168-177, 2010.
- [2] Vaidya B., Makrakis D. and Mouftan H. T., "Authentication and authorization mechanisms for substation automation in smart grid network," *IEEE Network*, vol. 27, pp. 5-11, Jan-Feb. 2013.
- [3] "Smart substations: a preliminary assessment," U.S. EPRI., Dec. 2001.
- [4] "Substation security and remote access implementation strategies," U.S. EPRI., 20-Dec-2012.
- [5] Shi Jing, Qi Huang, Jie Wu and Wei Zhen, "A novel whole-view test approach onsite commissioning in smart substation," *IEEE Trans. Power Deli.*, vol. 28, no. 3, pp. 1715-1722, 2013.
- [6] Ericsson G.N., "Cyber security and power system communication - essential parts of a smart grid infrastructure," *IEEE Trans. Power Deli.*, vol. 25, no. 3, pp. 1501-1507, 2010.
- [7] Xiaoling Jin, Yibin Zhang and Xue Wang, "Strategy and coordinated development of strong and smart grid," in *Proc. 2012 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, May 2012, pp. 1-4.
- [8] Jifeng Wang and Huafeng Zhou, "Conceptual design and the future development for operation smart system in China Southern Power Grid," *IEEE Trans. Smart Grid*, vol. 4, no.3, pp. 1621-1629, 2013.
- [9] Chen Jin-lun, Huang Chun, Zeng Zhao-xin, Qu Shuo, Luo Jiao and Qin Qian, "Smart grid oriented smart substation characteristics analysis," in *Proc. 2012 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, May 2012, pp. 1-4.
- [10] Salvadori F., Gehrke C. S., de Oliveira A. C., de Campos M. and Sausen P. S., "Smart grid infrastructure using a hybrid network architecture," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1630-1639, 2013.
- [11] Guangyu He, Sun Y., Qiang Lu, Li T., Hairong Lv, Wenjun Yin and Jin Dong, "Multi-index and self-approximate-optimal operation for a smart electrical power grid," *IBM Journal of Research and Development*, vol. 54, no. 6, pp. 2:1-2:14, 2010.
- [12] Erdal Kayacan, Baris Ulutas and Okyay Kaynak, "Grey system theory - based models in time series prediction," *Expert Systems with Application*, vol. 37, no. 2, pp. 1784-1789, Mar. 2010.
- [13] Pedryca W. and Mingli Song, "Analytic hierarchy process (AHP) in group decision making and its optimization with an allocation of information granularity," *IEEE Trans. Fuzzy Syst.*, vol. 19, no. 3, pp. 527-539, 2011.
- [14] "The technical bidding documents of Wenchongkou substation in CGS," EPRI. of Guangdong Power Grid Company, 2010.
- [15] IEC 61850-5 communication networks and systems in substations: Part 5 communication requirements for functions and device models, 2003.
- [16] IEC 61850-7 communication networks and systems in substations: basic communication structure for substations and feeder equipment, 2003.
- [17] IEC 61850-7 Edition 2.0 communication networks and systems for power utility automation: basic communication structure, 2010.
- [18] Ki-Baek Lee and Jong-Hwan Kim, "Multiobjective particle swarm optimization with preference-based sort and its application to path following footstep optimization for humanoid robots," *IEEE Trans. Evolutionary Computation*, vol. 17, no. 6, pp. 755-766, 2013.
- [19] Bernardon D. P., Sperandio M., Garcia V. J., Canha L. N., da Rosa Abaide A. and Daza E. F. B., "AHP

decision-making algorithm to allocate remotely controlled switches in distribution networks,” *IEEE Trans. Power Deli.*, vol. 26, no. 3, pp. 1884-1892, 2011.

- [20] H. T. Yang and S. L. Chen, “Incorporating a multi-criteria decision procedure into the combined dynamic programming/production simulation algorithm for generation expansion planning,” *IEEE Trans. Power Syst.*, vol. 4, no. 1, pp. 165-175, 1989.
- [21] T. L. Saaty and L. T. Tran, “On the invalidity of fuzzifying numerical judgments in the analytic hierarchy process,” *Math. Comput. Model.*, vol. 46, pp. 926-975, 2007.



Yi-Qun Song received her B.Sc., M.Sc. and Ph.D. degrees, all in Electrical Engineering, from Shanghai Jiao Tong University in 1992, 1995 and 2003, respectively. Her research interest is electricity market.



Dong Han received his M.Sc. degree from Harbin Institute of Technology in 2009. He is currently working towards the Ph.D. degree from Shanghai Jiao Tong University. He performs research on evaluation of smart grids and intelligent technology application as well as topics related to market operations in

electrical power systems.



Zheng Yan received his B.Sc., M.Sc. and Ph.D. degrees, all in Electrical Engineering, from Shanghai Jiao Tong University in 1984, and Tsinghua University in 1987 and 1991, respectively. He is a Professor in the Shanghai Jiao Tong University. His research interests

are application of optimization theory to power systems and dynamics security assessment.



Dao-Tian Zhang received the B.S.E.E. degree from Shanghai Jiao Tong University in 2013. He is currently working toward the M.Sc. degree at Shanghai Jiao Tong University. His research interests include the comprehensive evaluation of power systems.