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An End-to-End Network Evaluation Method for Differentiated Multi-Service Bearing in VPP

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ABSTRACT

Virtual power plant (VPP) plays an important role in improving the balance and regulation abilities of new power system. The safe and reliable operation is support by the VPP end-to-end communication network with differentiated multi-service bearing capability. For the requirement of unified and standard VPP end-to-end networking scheme, the VPP service communication metrics, as well as the communication network architecture of VPP aggregation and control are analyzed. Then, a multi-dimension hierarchical VPP end-to-end network evaluation index system is put forward. In addition, an end-to-end VPP network evaluation method considering differentiated time-sensitive and granular requirements of multiple services is proposed. Finally, the suitability analysis results of various end-to-end networking schemes and multiple services with differentiated time-sensitive and granular requirements are given, which plays a guiding role in establishing a unified standard VPP end-to-end networking scheme.

KEYWORDS

Differentiated Multi-Service Bearing, End-to-End Network, Granularity Requirements, Network Evaluation Method, Virtual Power Plant

Virtual power plant (VPP) integrates advanced information communication and intelligent metering technology to efficiently aggregate decentralized new energy power generation facilities, energy storage, and adjustable load, and it connects to the power grid to participate in peak regulation, frequency regulation and demand response to enhance the balance adjustment ability of the new power system (Bao et al., 2021; Y. Zhang et al., 2021). Since the interaction between distributed resources and grid through VPP aggregation involves distributed resource terminals (Liao et al., 2023), resource

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aggregators, and the information and multi-level coordination of the grid, the guaranteed ability of end-to-end quality of service (QoS) for VPP aggregation and regulation network is crucial for the safe and reliable operation of VPP.

In view of the differentiated time-sensitive and bandwidth granularity requirements of VPP service (Chen et al., 2021; Liao et al., 2022), VPP aggregation communication networks usually adopt high speed power line communication (HPLC), high speed radio frequency communication (HRF), 4G/5G, WiFi, optical fiber, and other communication modes to achieve heterogeneous networking. At present, most of the studies on VPP end-to-end networking schemes focus on heterogeneous network bearing schemes designed for specific engineering cases, and there is no unified standard scheme, which is not conducive to large-scale VPP development and subsequent promotion. Therefore, it is necessary to carry out the research on VPP end-to-end network evaluation technology to provide evaluation indices and performance analysis for the design of a VPP end-to-end network bearing scheme.

VPP end-to-end network evaluation includes the establishment of network evaluation indices, the appropriate comprehensive evaluation, and the sort of service carrying capacity for the end-to-end network. At present, there are few network evaluation studies considering the time sensitivity and granularity characteristics of VPP service differentiation. In one study by Jara et al. (2017), a blocking evaluation method of dynamic wavelength division multiplexing networks was studied, which considered different loads at each network connection. In a study by Yong et al. (2022), a novel analytical availability index calculation framework for adequacy evaluation was proposed based on the stochastic modeling to achieve the availability evaluation of the distribution network. In a study by Urgun et al. (2020), a new state classification approach to calculate power system reliability indices within the framework of the Monte Carlo simulation process is proposed to increase the scope and computational efficiency to evaluate reliability indices. The above documents consider indices such as real-time performance and reliability of the network; this helps to improve the rationality of the VPP end-to-end network index system but ignores the scalability of distributed resource aggregation regulation. In this, the comprehensiveness, objectivity, practicability, typicality, and standardization of the evaluation system still need to be further improved.

Research on evaluation methods of network bearing capacity mainly focuses on the analytic hierarchy process (Ge & Liu, 2019; Xiu et al., 2018; S. Zhang et al., 2016), the fuzzy analytic hierarchy process (Hao et al., 2019; Jiang et al., 2016; T. Wang et al., 2018), the Latin hypercube sampling method (Pan et al., 2018; Taghavi et al., 2022), etc. In a study by S. Wang et al. (2017), an electricity user evaluation method in smart electricity utilization was proposed. In another study by Bernardon et al. (2017), an AHP-based evaluation method for a device configuration scheme was proposed to effectively support operation planning of a low-voltage distribution station area. However, AHP can hardly reflect the ambiguity of subjective judgment. It is difficult to guarantee the consistency of the judgment matrix of AHP under a large number of evaluation indices. In a study by Dehghanian et al. (2017), a FAHP-based performance evaluation method was proposed to assess various types of components of monitoring devices in a low-voltage distribution station area. However, there still exist the following shortcomings: 1) the delay and granularity requirements of VPP multi-service differentiation are not considered; and 2) VPP end-to-end network includes remote communication and local communication, which involve a mixed networking of various communication modes. However, the existing evaluation methods evaluate only the service bearing capacity of local communication or remote communication, which cannot be applied to the bearing capacity evaluation of the VPP end-to-end network.

To solve the above problems, first, the multi-dimensional hierarchical VPP end-to-end network indices evaluation system for the differentiated multi-service bearing requirements is constructed in this paper. Secondly, the comprehensive weight is solved by the improved analytic hierarchy process (IAHP) and CRITIC, considering the demands of multi-service differentiation time sensitive. Then, the technique for order preference by similarity to an ideal solution (TOPSIS) is used to analyze the adaptability between different services and end-to-end network communication schemes, and this provides cases analysis to verify the feasibility of the proposed method. Meanwhile, the adaptability analysis results are provided for the design of end-to-end network bearing schemes for time-sensitive small-granularity, time-insensitive small-granularity, and time-insensitive large-granularity services.

VPP SERVICE COMMUNICATION REQUIREMENTS ANALYSIS AND AGGREGATION CONTROL COMMUNICATION NETWORK ARCHITECTURE

Analysis of VPP Service Communication Requirements

VPP services have the following characteristics: a large number of short-term services, a high concurrency rate, cross region services, and a large load fluctuation (Bian et al., 2020; Z. Liu et al., 2020). According to the different requirements of delay and bandwidth, VPP services can be divided into three types: time-sensitive small particles, time-insensitive small particles, and time-insensitive large particles. Their communication requirements are shown in Table 1 and are analyzed specifically through three typical applications.

They are analyzed through:

1. Frequency regulation: According to the automatic power generation control signal uploaded by the terminal in real time, VPP calculates the overall real-time power deficit of VPP and converts it into frequency regulation signal increment to realize frequency regulation response. Frequency regulation requires a communication bandwidth greater than 2Mbps and a communication delay of less than 50ms.
2. Peak regulation: VPP can integrate and dispatch the peak regulation resources on the demand side and participate in a form similar to traditional power plants in the peak regulation market. Its information source is mainly provided through energy storage charging, load increase, electric vehicle charging, and other ways. Peak regulating requires a communication delay of less than 10s and a communication bandwidth of less than 2Mbps.
3. Normal demand response: Normal demand response refers to the dynamic adjustment of the demand side's consumption pattern in the power market and its participation in the frequency regulation of the power grid, which is based on the electricity price and incentive policies. The delay requires less than 200ms, and the required communication bandwidth is from 0.01Mbps to 2Mbps.

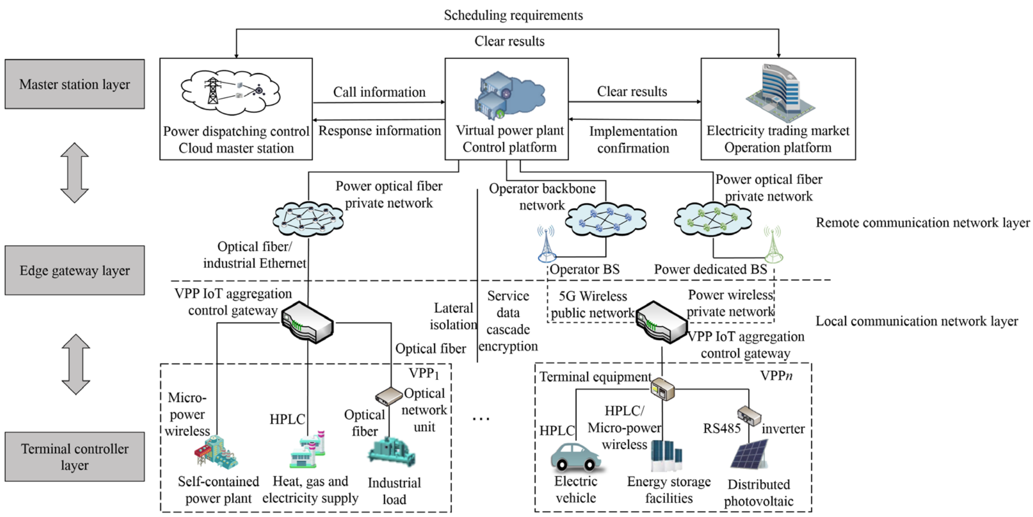
Communication Network Architecture of VPP Aggregation and Control

As shown in Figure 1, this section proposes the communication network architecture of VPP aggregation regulation based on the communication requirements of distributed source (Gu et al., 2018; Zhou et al., 2019; Zhu et al., 2019), load, and storage resources participating in power grid regulation through VPP aggregation. Communication network architecture of VPP adopts hierarchical architecture, which consists of a terminal controller layer, local communication network layer, edge gateway layer, remote communication network layer, and master station layer from bottom to top.

Table 1. Typical Service Communication Metrics of VPP

VPP Services	Services Type	Bandwidth	Delay
Frequency regulation	time-sensitive small particles	>2Mbps	<50ms
Peak regulation	time-insensitive small particles	<2Mbps	<10s
Normal demand response	time-insensitive large particles	0.01~2Mbps	<200ms

Figure 1. Communication Network Architecture of VPP Aggregation and Control



1. Terminal controller layer: It covers demand-side energy terminals such as photovoltaic panels, electric vehicles, energy storage equipment, and on/off-grid equipment such as inverters. It also involves VPP data acquisition terminals such as temperature, light, voltage, and current sensors.
2. Local communication network layer: It contains HPLC, RS485, HRF, and other access modes. The terminal controller layer uploads service data to the edge gateway layer through the multi-medium communication modes of the local communication layer.
3. Edge gateway layer: By deploying VPP Internet of Things aggregation control gateway, the distributed resources are aggregated to participate in the collaborative regulation of the power grid and are responsible for the aggregation, cleaning, and uploading of service data within the jurisdiction.
4. Remote communication network layer: It mainly adopts optical fiber, 4G/5G public network, power wireless private network, and other communication technologies to realize interconnection among multiple platforms, providing a data path for reliable aggregation and uploading of wide-area service data to the power grid. The communication layer and the platform layer are based on hierarchical encryption authentication of service data to protect the confidentiality and integrity of data transmission. Optical fiber communication networks in different security zones and 4G/5G public networks are physically isolated based on lateral isolation devices.
5. Master station layer: It contains integrated power grid dispatching cloud platform, VPP platform, and power trading market operation platform, bringing together power grid operation and maintenance, security, and distributed resource operation data and realizing the mining of distributed resource regulation potential based on big data, artificial intelligence, and other advanced technologies; this also conducts dynamic aggregation management and collaborative scheduling of distributed resources through cloud-edge collaboration.

Communication network architecture of VPP aggregation and control contains a variety of communication media. VPP services have great differences in time delay and bandwidth particle requirements. There exists no unified standard scheme on which an end-to-end network bearing mode should be adopted. Therefore, in order to meet the requirements of constructing the VPP end-to-end network bearing scheme with differentiated multi-service bearing, the article first carries out the evaluation index system with comprehensiveness, objectivity, practicability, representativeness, and standardization. The method of VPP end-to-end network evaluation considering the time-sensitivity and granularity requirements of multi-service differentiation is proposed based on this index system to support the construction of a unified standard VPP end-to-end bearer scheme.

MULTI-DIMENSIONAL HIERARCHICAL VPP END-TO-END NETWORK EVALUATION INDEX SYSTEM

In this section, the authors propose an evaluation index system for a VPP end-to-end network. First, the authors introduce the evaluation indices framework. Secondly, they describe the individual indices respectively.

Evaluation Index Framework

Based on VPP aggregation control communication network architecture and the principle of comprehensiveness, objectivity, practicality, typicality, and standardization, a multi-dimension hierarchical VPP end-to-end network evaluation index system is constructed, as shown in Figure 2, that fully takes the differentiated requirements of various communication media and VPP services in terms of delay and bandwidth into account. The traditional network evaluation index system mainly focuses on the aspects of network timeliness, reliability, cost-effectiveness, etc., which ignores the scalability of the network. However, distributed resources participate in power grid regulation through VPP aggregation, resulting in a significant increase of network dynamics, which therefore makes scalability an important indicator to measure the performance of VPP communication networks (Don et al., 2020; Jun et al., 2021). To this end, the authors add several scalability indices such as multi-service access adaptability, technology maturity, and networking flexibility to describe communication performance of the VPP end-to-end network.

Individual Index Introduction

Real-Time Index

The real-time index mainly evaluates the end-to-end network communication performance of VPP, which specifically describes end-to-end delay, end-to-end jitter, communication bandwidth, transmission distance, transmission rate, and end-to-end throughput. Moreover, end-to-end delay contains three segments (i.e., local communication delay, remote communication delay, and bridge partial delay) between the two ends of communication networks.

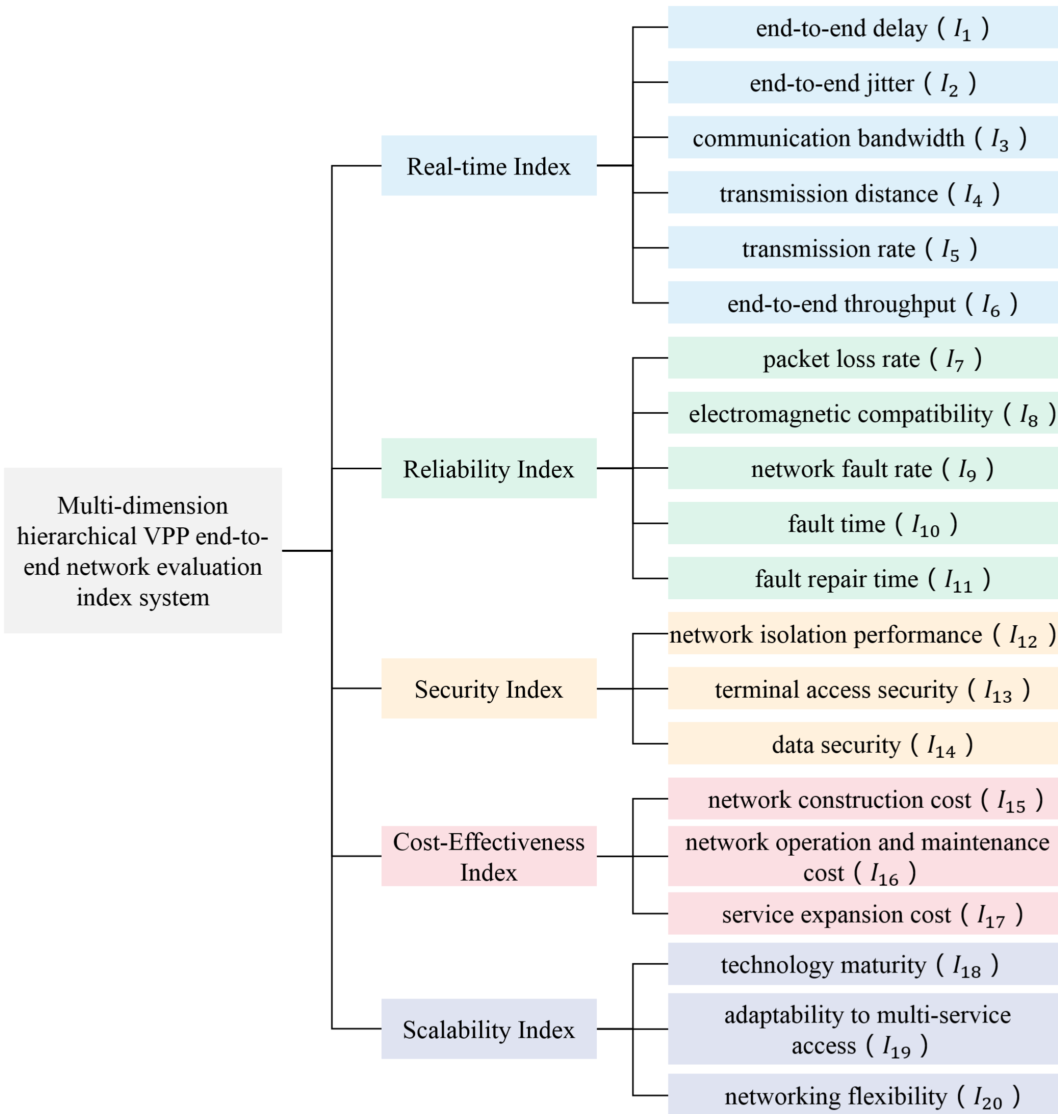
Reliability Index

The reliability index demotes the basic communication performance of the VPP end-to-end network, which specifically describes packet loss rate, electromagnetic compatibility, network fault rate, fault time, and fault repair time. The authors evaluate the reliability index by the sequential Monte Carlo method. Moreover, network fault rate refers to the comprehensive fault rate of the entire VPP end-to-end network, including the master station layer, edge gateway layer, and terminal controller layer.

Security Index

The security index mainly evaluates the ability of the end-to-end VPP network to resist external interference and ensure the secure transmission of VPP-related service data. The security index includes network isolation performance, terminal access security, and data security. To be specific, network isolation performance depends on local communication, remote communication, and the least isolated part of the two-segment communication network bridging process.

Figure 2. Multi-Dimension Hierarchical VPP End-to-End Network Evaluation Index System



AN END-TO-END VPP NETWORK EVALUATION METHOD CONSIDERING DIFFERENTIATED TIME-SENSITIVE AND GRANULAR REQUIREMENTS OF MULTIPLE SERVICES

Based on the VPP end-to-end network evaluation index system, this section first introduces the comprehensive weight solution of the VPP end-to-end network suitability analysis index. Then, the suitability analysis of VPP end-to-end network bearing solutions is performed using TOPSIS.

Suitability Analysis of Comprehensive Weight Solution of the Indices

The rationality of the VPP end-to-end network suitability analysis index weights has a crucial impact on the credibility of the suitability analysis results. The unilateral adoption of subjective or objective weighting models is one-sided and affects the credibility of evaluation results. Therefore, this paper adopts the IAHP and CRITIC methods to derive the subjective and objective weights respectively.

Solution of Subjective Weight

Traditional AHP methods often fail to make decisions when performing weight analysis due to the non-satisfaction of consistency of the judgment matrix, which leads to difficulties in the actual evaluation process. In this paper, the authors adopt the IAHP method to solve the above problem and use the scalar construction method to directly construct the judgment matrix that satisfies the consistency, which greatly improves the evaluation efficiency.

The consistency judgment matrix $\boldsymbol{S}=(s_{i,j})_{n\times n}$ of the VPP end-to-end network suitability analysis satisfies the following conditions: 1) $s_{i,j} > 0$; 2) $s_{i,i} = 1$; 3) $s_{i,j}=1/s_{j,i}$; and 4) $s_{i,j} = s_{i,k}s_{k,j}$, where element $s_{i,j}$ reflects the importance of index i versus index j. All indices are subjectively ranked according to the principle of non-decreasing importance, and this is used to determine the relative importance of the i-th index and the $\left(i+1\right)$-th index. The elements of the consistency judgment matrix $\boldsymbol{S}$ can be given according to the transferability of index importance by:

$$s_{i,j} = \begin{cases} \prod_{p=i}^{j-1} t_p,\ i < j \\ 1,\ i = j \\ \dfrac{1}{\prod_{p=j}^{i-1} t_p},\ i > j \end{cases}. \tag{1}$$

Then, based on the above consistency judgment matrix, the subjective weights ω_i^{sub} for each index are calculated as:

$$\omega_i^{sub} = \frac{\sqrt[n]{\prod_{j=1}^{n} s_{i,j}}}{\sum_{i=1}^{n} \sqrt[n]{\prod_{j=1}^{n} s_{i,j}}}. \tag{2}$$

Solution of Objective Weight

The objective weights of the indices not only consider the amount of the information it contains, but also fully take into account the comparison between different VPP end-to-end network solutions and the conflict between evaluation indices, thus making the weights more objective.

The network property matrix can be constructed as $\boldsymbol{X} = \left(x_{i,j}\right)_{n\times m}$ based on the performance of n indices of VPP services under m different communication schemes. At the same time, considering that the solution of objective weights needs indices data support, the indices in the text should be transformed into dimensionless data, and the indices data should be normalized to the range of [0,1] in order to obtain the dimensionless network property matrix $\boldsymbol{G} = \left(g_{i,j}\right)_{n\times m}$, whose elemental expressions can be given by:

$$g_{ij} = \frac{x'_{i,j}}{\sqrt{\sum_{j=1}^{m}(x'_{i,j})^2}}, \quad i = 1,2,\cdots,n, \tag{3}$$

$$x'_{i,j} = \begin{cases} \dfrac{1}{\max\left|\boldsymbol{X}_i\right| + x_{i,j}}, & \text{cost-type index,} \\ x_{i,j}, & \text{benefit-type index,} \end{cases} \tag{4}$$

where, for the cost-type index, a larger value indicates better performance; while for the benefit-type index, a smaller value indicates better performance.

Finally, the amount of information ψ_i contained in each index is calculated based on the dimensionless network property matrix $\boldsymbol{G}$, which is given by:

$$\psi_i = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(g_{i,j} - \bar{g}_i)^2}\sum_{j=1}^{n}(1 - \frac{\text{cov}(\boldsymbol{G}_i, \boldsymbol{G}_j)}{\alpha_i\alpha_j}). \tag{5}$$

The greater the amount of information ψ_i contained in the index, the greater the weight of the index. Therefore, the objective weight ω_i^{obj} of the indicators is given by:

$$\omega_i^{obj} = \frac{\psi_i}{\sum_{j=1}^{n}\psi_j}. \tag{6}$$

Solution of Comprehensive Weight of the Indices

The subjective and objective weight vectors $\boldsymbol{\omega}^{sub}$ and $\boldsymbol{\omega}^{obj}$ are obtained from the IAHP and CRITIC methods, respectively. In order to make the comprehensive weights ω_j as close as possible to ω_j^{sub} and ω_j^{obj} without favoring any of them, the comprehensive weight of the index based on the principle of minimum information discrimination is given by:

$$\begin{aligned} &\min F(\boldsymbol{\omega}) = \sum_{i=1}^{n}\left(\omega_i \ln\frac{\omega_i}{\omega_i^{sub}} + \omega_i \ln\frac{\omega_i}{\omega_i^{obj}}\right), \\ &s.t.\ \sum_{i=1}^{n}\omega_i = 1. \end{aligned} \tag{7}$$

By solving the above problem, the authors can obtain the comprehensive weight of index as:

$$\omega_i = \frac{\sqrt{\omega_i^{sub}\omega_i^{obj}}}{\sum_{j=1}^{n}\sqrt{\omega_j^{sub}\omega_j^{obj}}}. \tag{8}$$

In this case, the comprehensive weight vector of indices is $\boldsymbol{\omega}=[\omega_1,\omega_2,\cdots,\omega_n]$.

TOPSIS-Based Suitability Analysis

After calculating the comprehensive weights of indices, the evaluation results obtained by direct linear solution ignore the functional relationship between the comprehensive index values and each index, which makes it difficult to ensure the accuracy and rationality of the evaluation results. Therefore, this paper adopts the improved TOPSIS method to evaluate each solution, which solves the solution ranking problem based on the relative approximation of each solution to the ideal solution.

The weighted adaptability analysis matrix $\boldsymbol{H}$ is calculated based on the comprehensive weight $\boldsymbol{\omega}$ of the index and the dimensionless network property matrix $\boldsymbol{G}$ as:

$$\boldsymbol{H}_i = \boldsymbol{G}_i\omega_i, \tag{9}$$

where $\boldsymbol{H}_i$ represents the row vector of matrix $\boldsymbol{H}$.

Based on the weighted suitability analysis matrix $\boldsymbol{H}$, the maximum value of each index is taken to form the positive ideal solution $\boldsymbol{H}^+=[h_1^+,\cdots,h_j^+,\cdots,h_n^+]$, and the minimum value of each index is taken to form the negative ideal solution $\boldsymbol{H}^- = [h_1^-,\cdots,h_j^-,\cdots,h_n^-]$.

The projection of each solution on the reference standard (i.e., the relative approximation) is used as the basis for judging the superiority of the solutions by taking the positive and negative ideal solutions as the reference standards, respectively. The relative approximation C_j between each solution and the positive and negative ideal solutions are given by:

$$C_j = \frac{\boldsymbol{H}^+ \cdot \boldsymbol{H}_j}{\sqrt{(\boldsymbol{H}^+)^2}} - \frac{\boldsymbol{H}^- \cdot \boldsymbol{H}_j}{\sqrt{(\boldsymbol{H}^-)^2}},\ j = 1,2,\cdots,m. \tag{10}$$

The greater the relative approximation, the closer the solution is to the ideal solution, indicating that the solution is optimal.

Cost-Effectiveness Index

The cost-effectiveness index refers to the capability that under the guarantee of certain network communication performance, end-to-end VPP network resources are fully utilized and cost as well as loss are effectively controlled. It mainly includes network construction cost, network operation and maintenance cost, and service expansion cost. Considering the uncertainty of technical and economic variables, this paper carries out economic evaluation based on the full life cycle of the network to obtain sufficient decision information. Specifically, the service expansion cost refers not only to the terminal service expanding cost but also to the service expansion cost of all sides, including terminal, network management, and primary station.

Scalability Index

The scalability index refers to the potential of whether the VPP end-to-end network can adapt to the development of future services according to current economic and environmental conditions as well as future uncertainties. In the maturity of communication technology applied in the VPP end-to-end network lies an important emphasis on network scalability. On the other hand, the flexibility of networking and adaptability of service access also reflect the scalability of the VPP end-to-end network in terms of hardware and software. Technology maturity, adaptability to multi-service access, and networking flexibility are also important guidelines for future development and become three main segments of the scalability index. Moreover, the technology maturity spans the whole network, which includes the data acquisition, transmission, and processing technology on the sides of terminal controller, edge network management, and primary station.

In the proposed multidimensional hierarchical evaluation index system of the VPP end-to-end network, some indices (e.g., end-to-end delay, communication bandwidth, and packet loss rate) can be obtained by laboratory simulation. For the indices that are difficult to acquire by simulation, this paper constructs an evaluation system to obtain corresponding data by expert evaluation.

CASE STUDY

Based on the proposed method, the subjective weights of each index are solved by constructing the consistency judgment matrix according to the scalar construction method. Then the objective weights of the indices are calculated by the CRITIC method, and the comprehensive weights are obtained by the principle of minimum information fusion. Finally, on the basis of the weighted adaptability analysis matrix, the comprehensive evaluation value of the scheme is solved by the improved TOPSIS method. The following six schemes are considered in this paper.

1. Scheme 1: HPLC is used for local communication, and 5G is used for remote communication.
2. Scheme 2: HPLC is used for local communication, and a private power fiber optic network is used for remote communication.
3. Scheme 3: HPLC + micropower wireless/WiFi are used for local communication, and 5G is used for remote communication.
4. Scheme 4: HPLC + micropower wireless are used for local communication, and xPON is used for remote communication.
5. Scheme 5: Micro power wireless is used for the local communication mode, and xPON is used for remote communication.
6. Scheme 6: Micro power wireless is used for local communication, and 5G is used for remote communication.

The authors constructed a VPP end-to-end simulation platform to simulate the six schemes mentioned above. Based on the simulation results, real-time, reliability, and security metrics for each scheme were obtained. Simultaneously, the authors invited relevant experts to evaluate the cost-effectiveness and scalability of each proposed scheme.

Taking peak shaving, frequency regulation, and normal demand response services as examples, according to Equations (1) through (8), their real-time evaluation index weights are presented in Table 2. Among them, objective metrics such as end-to-end delay, delay jitter, and packet loss rate are obtained based on the VPP end-to-end simulation platform. Problem: 1-6: Taking Scenario 1 as an example, the VPP end-to-end simulation platform is built based on the INET component in OMNET++ (Inzillo et al., 2019), and the end-to-end delay of device accessing to the VPP master station is measured. Figure 3 shows the end-to-end delay composition of device accessing to the VPP master station obtained based on the built VPP end-to-end simulation platform. The terminal data is accessed by the VPP master station through the device, VPP IOT aggregation control gateway, operator router, and power transmission network channel formed by the power company router and security access zone. The end-to-end communication delay is 150~350ms. Among them, the local communication delay is 60~80ms, the operator 5G network slice delay is 13~19ms, and the power transmission network channel transmission delay is 10~14ms.

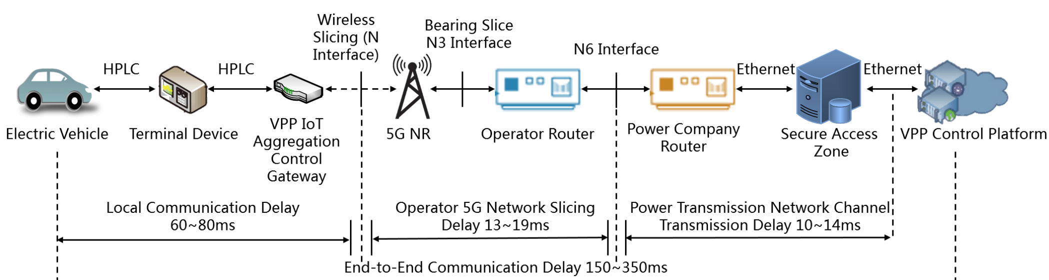
The performances of the six end-to-end communication schemes are scored in terms of real-time indices and reliability indices, as shown in Table 3. The performance analysis and applicable services of the end-to-end networking schemes are shown in Table 4.

Based on the index scores and weights, the results of the suitability analysis of the three services of peak shaving, frequency regulation, and normal demand response with various VPP

Table 2. VPP End-to-End Network Evaluation Indicator Weight

Services	First-Level Index Weight	Second-Level Index Weight
Peak regulation	Real-time index 0.327	End-to-end delay 0.204
		End-to-end jitter 0.131
		Communication bandwidth 0.109
		Transmission distance 0.145
		Transmission rate 0.156
		End-to-end throughput 0.255
Frequency regulation	Real-time index 0.278	End-to-end delay 0.195
		End-to-end jitter 0.143
		Communication bandwidth 0.136
		Transmission distance 0.155
		Transmission rate 0.154
		End-to-end throughput 0.217
Normal demand response	Real-time index 0.272	End-to-end delay 0.171
		End-to-end jitter 0.104
		Communication bandwidth 0.187
		Transmission distance 0.124
		Transmission rate 0.128
		End-to-end throughput 0.286

Figure 3. The End-to-End Delay Composition of the Device Accessing to the VPP Control Platform



end-to-end networking schemes are shown in Table 5. According to the results in the table, frequency regulation, peak shaving, and normal demand response services have the strongest adaptability with Scheme 2, Scheme 4, and Scheme 3, respectively, which is consistent with the results analyzed in Table 4.

Finally, the method proposed in this paper is compared with the existing methods mentioned in the introduction, such as the hierarchical analysis, fuzzy hierarchical analysis, and Latin hypercube sampling method, and the results of the comprehensive adaptability analysis by many experts are used as the benchmark; the specific comparison results are shown in Table 6. It can be seen that the proposed method can realize the high accuracy rate adaptability analysis of three types of services, namely, frequency regulation, peak shaving, and normal demand response services, and can provide guidance for the end-to-end network construction of VPP with differentiated multi-service.

CONCLUSION

In this paper, the authors proposed a VPP architecture of the aggregation regulation communication network based on the design requirements of the end-to-end network for differentiated multi-service bearing in VPP. The differentiated time-sensitive and bandwidth granularity requirements of peak regulation, frequency regulation, and demand response were analyzed. Moreover, the multi-dimensional hierarchical VPP end-to-end network evaluation index system was constructed, and the VPP end-to-end network evaluation method based on the requirements of multi-service differentiated time sensitivity and granularity was proposed. In the case study, peak regulation, frequency regulation, and demand response were selected to stand for the time-sensitive small-granularity, time-insensitive small-granularity, and time-insensitive large-granularity services. And the simulation results indicate that the proposed method achieves high accuracy in adaptability analysis for three types of services: frequency regulation, peak shaving, and normal demand response services, with accuracies of 95.4%, 96.2%, and 95.8%, respectively. Besides, the adaptability of various VPP end-to-end networking schemes has been given; this plays a certain guiding role in establishing a unified standard VPP end-to-end networking scheme.

Table 3. End-to-End Communication Scheme Score

First-Level Index Weight	Second-Level Index Weight	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6
Real-time index	End-to-end delay	91.500	93.600	95.580	88.640	83.500	90.350
	End-to-end jitter	73.500	89.350	75.100	82.750	85.600	79.680
	Communication bandwidth	91.100	92.650	93.500	83.850	80.750	90.950
	Transmission distance	87.450	87.550	89.610	90.900	89.550	85.960
	Transmission rate	91.950	83.450	92.360	86.150	80.960	89.880
	End-to-end throughput	88.860	82.550	89.120	85.100	81.500	86.450
Reliability index	Packet loss rate	83.070	88.907	91.991	90.173	88.432	86.878
	Electromagnetic compatibility	84.090	88.908	85.573	89.651	90.982	87.127
	Network failure rate	86.901	82.373	89.093	84.884	85.251	87.045
	Failure time	89.021	85.034	91.756	87.492	83.867	88.085
	Fault repair time	87.683	83.174	91.231	84.531	86.731	89.423

Table 4. Applicability Analysis of End-to-End Networking Scheme

Scheme	Performance Analysis	Application Scenario
HPLC+5G	Advantages: Support large bandwidth, low delay and wide connection, strong anti-interference capability, good communication performance. Disadvantages: High cost, the security of 5G hard slice bearing regulatory services security needs to be verified.	1) The load and energy equipment send the collected data to the terminal equipment; 2) Data transmission from centralized control device to VPP master station dispatching cloud
HPLC+Power optical fiber private network	Advantages: High bandwidth support, low delay, strong anti-interference ability, wide coverage (more than 20km), mature technology, high security, and reliability. Disadvantages: High ratio of master to slave nodes in the current power grid leads to low transmission rate.	
HPLC+Micropower wireless/WiFi+5G	Advantages: Moderate coverage, bandwidth, time delay, and reliability meet most local communication service scenarios. Disadvantages: Use shared common wireless frequency band, and security and anti-interference capability need to be improved.	1) The terminal device will collect data; 2) The load and energy equipment send the collected data to the centralized control equipment; 3) The centralized control device sends the control instruction to the terminal device; 4) Centralized control device to VPP master station dispatching cloud
HPLC+Micropower wireless+xPON	Advantages: Independent and controllable technology, no intellectual property risk, strong anti-interference ability, mature technology, high security, and reliability. Disadvantages: High security and reliability. Disadvantages: High ratio of master to slave nodes in the current power grid leads to low transmission rate and high one-time investment cost.	
Micropower wireless+xPON	Advantages: Moderate coverage, low transmission delay, mature technology. Disadvantages: Limited bandwidth and transmission distance, high one-time investment cost.	
Micropower wireless+5G	Advantages: Support large bandwidth, low delay, and wide connection and has relatively low cost without grid operation and maintenance. Disadvantages: High cost and the security of 5G hard slice bearing regulatory services needs to be verified.	

Table 5. Adaptability Analysis Results

Services	Adaptability Score						Results of Adaptation Analysis
	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6	
Frequency regulation	85.040	89.500	80.100	83.250	68.500	86.350	Scheme 2
Peak regulation	77.156	73.943	81.660	89.198	86.253	83.426	Scheme 4
Normal demand response	80.650	90.130	93.120	75.560	91.050	88.500	Scheme 3

Table 6. Comparison of the Accuracy of Adaptability Analysis of Different Methods

Services	Different Methods			
	Proposed Method	Analytic Hierarchy Process	Fuzzy Analytic Hierarchy Process	Latin Hypercube Sampling Method
Frequency regulation	95.4%	83.4%	86.8%	83.2%
Peak regulation	96.2%	85.2%	84.4%	82.8%
Normal demand response	95.8%	84.0%	86.2%	85.6%

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COMPETING INTERESTS

The authors of this publication declare there are no competing interests.

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