Risk-Aware Service Routes Planning for System Protection Communication Network in Energy Internet

Baoju Liu[1], Peng Yu[1*], Fangzheng Chen[2], Fang Chen[3], Qiu Xue-song[1], Lei Shi[4]

[1]State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications Beijing 100876, China

[2] State Grid Information and Telecommunication Branch, Hebei Province 100876, China

[3] State Grid Information and Telecommunication Branch, Beijing 050000, China

[4]Department of Computing, Carlow Institute of Technology, Carlow, Ireland

Corresponding Email:yupeng_bupt@126.com

***Abstract*—Energy Internet (EI) is the advanced stage of smart grids (SG). To guarantee collaborative operations of subsystems in EI, it requires the assistance of high-performance system protection communication network (SPCN). As an emerging networking paradigm, software-defined networking (SDN) is applicable to the communication architecture construction of SPCN due to the advantage of rapid routing convergence owing to the global topology of SDN controller and logical centralized architecture. With the purpose of continuous transmission for services and stable operations of EI, dual routes are urgent to be pre-planned so that fast switching can be achieved from a failed primary route to an alternate route for interrupted services. However, it is a challenge to balance service end-to-end delay and the network operation risk for the existing routing strategies. In light of few studies combining network risk with service QoS, we propose a novel risk-aware routes planning mechanism (RSRM) to reduce network risk as well as guarantee critical service performance of SPCN. The mechanism is based on solving the bi-objective problem to minimize the effect of network risk and potential delay of routes simultaneously. The formulated problem is NP-hard, so a multi-objectives computational intelligent approach is exploited. Simulation results demonstrate that our method effectively reduces the balancing risk of the network and obtain the minimal total end-to-end delay in comparison with other algorithms.**

Keywords—Energy Internet, Smart Grid, SPCN, RSRM, SDN

I. INTRODUCTION

With the implementation of Ultra/Extra High Voltage AC/DC Projects and integration of renewable resources synchronization (e.g., wind, solar, hydro), smart grids are evolving into the stage of Energy Internet (EI), where electrical energies from various sources across different regions are piped into the same network for better resource utilization [1]. EI is the combination of information and communication technology (ICT) as well as the energy system. The safe and stable operations are essential to EI. However, the traditional protection strategy based upon local information in smart grids can hardly achieve smooth operations of EI due to its larger scale and complex structure. Therefore, the concept of system protection (SP) has been proposed targeting coordinated and stable operations of the subsystems according to the global real-time information tagged as control services [2]. SP functions heavily rely on the system protection communication network (SPCN) which transfers various control services (e.g., for instance, AC/DC control services, pumped storage control services) and panoramic perception services.

Taking the panoramic perception service as an example, to monitor and analyze the status of EI, SP should perceive power generation, transmission, distribution, and DC system panoramic perception within 60ms and deal with the important disturbance in 300ms, and the bandwidth requirement is 20Mbit/s [3]. If the above operations are not performed timely, power flows transferring, or even worse, power outages may happen [4]. Although the dedicated lines on basis of point to point mode can better meet the needs of rigorous latency, it is not realistic to connect all of substations in this method. High-performance communication networks with reliable and fast failure recovery ability need to be built. Due to the efficient and flexible control over network devices with a global view, SDN-based IP networks provides the possibility for panoramic perception service with stringent latency and high bandwidth requirements, especially the significant improvements of convergence time in the case of failures. Meanwhile, there is an ongoing trend of switching control services from the dedicated lines to the SDN-based IP networks. The minimum round trip time (RTT) is about 30ms through the implementation of the PLC modem in SDN-based heterogeneous IP networks [5]. Therefore, the SDN-based communication architecture is applied in the SPCN.

Given the importance of control services and panoramic perception services to EI and the design of N-1, dual routes are urgent to be pre-planned so that fast switching can be achieved from a failed primary route to an alternate route for interrupted services. Further, services in SPCN usually aggregate from the executive stations to the master stations or the control center, which leads to some critical links/devices overload and increases the additional risk of EI. Therefore, ensuring service evenly distributed in SPCN and service QoS is still a challenge for routes planning. [6-9] provided various multi-path routing algorithms based on energy efficiency, resources allocation or the changes of network topology but they did not consider the impact of different service factors. To the best of our knowledge, up to now, there are few studies about routes planning combining service distribution with service QoS, we propose a novel risk-aware routes mechanism (RSRM) to ensure the deliverability and timeliness of critical services in EI.

To summarize, the key contributions of our work are as follows.

978-3-903176-15-7 © 2019 IFIP

1) We formulate service-aware routes planning as a multi-objective optimization problem with the purpose of minimizing the balancing risk of the network and the total end-to-end delay for all services simultaneously while satisfying the requirements of link bandwidth and latency.

2) We present a novel routing mechanism to solve the optimization problem in combination with the system operation. The effectiveness of the mechanism is validated in a field network with an intelligent algorithm. Simulation results demonstrate it can better achieve a tradeoff between the balancing risk of the network and service QoS than other approaches.

The remainder of this paper is organized as follows. Section II reviews the related work. Section III describes the communication architecture of EI based on SDN and formulates the system model. Section IV provides explicit modules of RSRM. Section V presents the details of NSGAII. Simulation results and comparative analysis are presented in Section VI and this paper is concluded in Section VII.

II. Related Work

Currently, to ensure service reliability in traditional power communication networks, a self-healing loop based on link switching and multiplex section switching is the most popular scheme for its rapid recovery. Various ring protection schemes are studied in [10,11]. However, latency discrepancies in bidirectional links restrict its application in the sparse network. Moreover, the ring structure is prone to be affected by the optical fiber and device failures, which increases service interruption probability and decreases service dependability.

Currently, researchers concentrate on improved algorithms based on Dijkstra, Floyd, and Bell-Ford or various intelligent algorithms to realize more reliable service routing. Dong et *al.* studied the service routing construction approach in the cyber-physical power system (CPPS) based on risk balance and risk probability of cross space with a genetic algorithm [12]. Cai et *al.* introduced a routing planning approach using NSGAII oriented to the overall services by jointly optimizing two objectives (i.e., the average network risk, the risk balancing of the network while neglecting service QoS requirements [13]. Zeng et *al.* analyzed communication service importance, the average risk of network and the balanced risk of network and then calculate the top *k* shortest paths for the individual service, afterward, the most balanced risk path in the network was chosen as the primary path according to the principle of Min-Max [14]. However, they did not provide a definite way to determine the upper bound of *k*. Hence, it is difficult to ensure that the chosen path is globally optimal.

In SDN paradigm, there is significant work about different routing algorithms at present. Aiming to energy-aware routing in a scenario of progressive migration from legacy to SDN hardware, the authors proposed SENAtoR algorithm to reduce the energy consumption of ISP networks [7]. In order to ensure end-to-end latency for each traffic flow based on the queue support in OpenFlow and efficiently allocate network resources in terms of user's demand, a solution which explored the strength of multi-path routing with a precise bandwidth allocation was presented in [8]. Hu et *al.* [15] proposed a tree-like hierarchical routing architecture which employed the divide-and-conquer strategy to enhance routing performance on the distributed control plane. They took into account the response time of routing request, queue stability based on queuing theory and resources constraint. To avoid silent failures, the authors provided a method of alternate routes on SDN similar to a binary search where suspicious nodes and links are pruned gradually on until the alternative route was found within the allowable delay [9]. The above work concentrates on energy efficiency, resources allocation, networking topology, but no consideration of service features in the SDN paradigm.

Different from the related work, we focus on reliable service routes planning based on service risk as well as service QoS, which play an important part role in safe and stable operation of EI.

III. Communication Architecture and System Model

A. *Communication Architecture for EI based on SDN*

Software-Defined Networking (SDN) is an emerging network architecture which decouples the software from the hardware devices. It can flexibly change or configure service routing dynamically according to service requirements. SDN-based architectures applied for smart grid communications have been widely studied in [16-18]. A layered communication architecture based on SDN is shown in Fig. 1 for EI [18,19]. It consists of three parts: data plane, control plane, and application plane. The communication among these parts is controlled by an application programming interface (API) and the OpenFlow protocol.

At data plane, a heterogeneous/hybrid communication network is formed from the aspects of energy demand and energy supply. Energy demand contains residents, factories, and electric vehicles, and energy supply includes power generation, solar electricity, wind turbine, and energy storage. Thus, a wide area grid is constructed to enable the energy and information exchange among different regions. Various energy demands and energy supplies connected through end gateways are data requesters by SDN switches, which are sent and received to and from the control unit, i.e., a local controller center (LCC). At the back end, a master control center (MCC) and the data unit (data servers) are deployed to analyze, control and monitor the data.

At control plane, a global SDN controller is in charge of control and data units to perform the following functions, topology discovery, network service management, routing management, and virtualization management. SDN controller software i.e., network operating system is installed at control plane. SDN controller is a logically centralized entity which makes intelligent decisions and helps administrators to modify network policies dynamically. A hypervisor is used by network function virtualization (NFV, which can disintegrate a larger physical network into multiple smaller logical networks) to produce multiple virtual resources that can concurrently run various applications. Multiple virtual controllers are created as an instance of the physical controller by virtualization. A physical controller is a primary controller and multiple virtual controllers are the backup controllers to support multiple applications running simultaneously. The multiple controllers are connected to each other through eastbound and westbound APIs. They are connected to the forwarding devices through southbound APIs.

The uppermost part is the application plane mainly including wide area measurements (WAMS), distribution management system (DMS), meter data management system (MDMS), etc. Control services, protections, and measurements delivered from backbone SDN switches, which help flexibly maintain smooth operation of the communication network for EI.

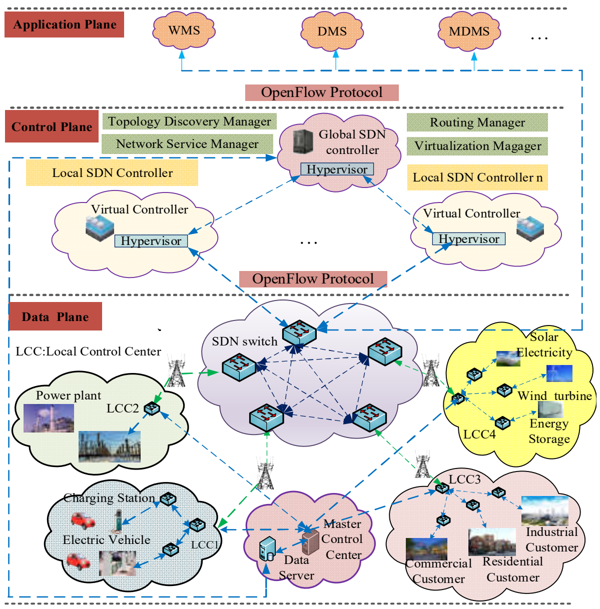


Fig. 1. Communication Architecture of EI based on SDN.

To illustrate the problem clearly, the symbols appeared in the paper are shown in Table I.

TABLE I. NOMENCLATURE

Symbol	Definition
V; E; S	Node set; Edge set; Service set
s_k; I_k	The k^{th} service in S; s_k importance, $s_k \in S$
P_S ; $p_s(k)$	Service route set; Route of s_k, $p_s(k) \in P_S$
D_i^v; D_{ij}^e	Risk of v_i, e_{ij} ,$v_i \in p_k(s)$,$e_{ij} \in p_k(s)$
N_i^v; N_{ij}^e	Importance of v_i Edge importance of e_{ij}
P_i^v; P_{ij}^e	Failure probability of v_i and e_{ij}
D_{avg}^V; D_{avg}^E	Average node risk; Average edge risk
D_{BRS}	Balancing risk of the network
T_k^p	End-to-end delay of $p_k(s)$
T_{total}	Total end-to-end delay of all services
$p_s^b(k)$; $p_s^a(k)$	The primary and alternate route of s_k , $p_s^a(k) \in P_S$
Λ_k	Intersection of dual path of service s_k

B. System model

We model SPCN as a graph $G=(V, E)$. Various secondary SDN devices installed in various substations or the dispatching center are abstracted to a node set V and communication links are abstracted to an edge set E. n and m are the cardinalities of V and E, i.e., $n=|V|$, $m=|E|$, respectively. S is the service set in need of routes planning, $S=\{s_1, s_2,\ldots s_k,\ldots\}$, where s_k is the k^{th} service in S. A triplet ($v_h(k)$, $v_d(k)$, I_k) depicts a service requirement, where $v_h(k)$, $v_d(k)$ are the source node and the destination node of s_k, and $v_h(k) \in V$, $v_d(k) \in V$. I_k indicates the importance of s_k, the more important s_k, the larger I_k. For the adjacency matrix X=[x_{ij}], x_{ij} equals 1 if there is an edge between v_i and v_j, and 0 otherwise. Service route set is P_S. The route for any s_k can be represented as $p_s(k)=(v_h(k),\ldots v_i(k),\ldots,v_d(k))$, where $p_s(k) \in P_S$.

Node risk model. Node risk describes the influence over the network because of node failure occurrence. Since EI covers a wider geographic area and spreads over a long distance up to 5,000 kilometers, dozens or hundreds of secondary devices are involved. Exposure to the harsh environment, devices are prone to break down for human incidents or natural disasters. Node risk is related with the node failure probability, the node importance, and the service importance carried on the node.

For simplicity, node failure probability can be calculated according to the following formula: $P_i^v = C_i^v / T$, where C_i^v is fault times of node v_i in unit time, which can be obtained from the statistics of networking management system. T is the observation time (e.g., one year, one month). Meanwhile, Node importance depends upon the voltage level and the scale of the substation. The higher voltage level and the larger scale, accordingly, the greater risk in the case of node failure occur [20]. Node importance can be acquired in terms of voltage level using the principle of min-max, and a dispatching center has the largest node importance. Additionally, the more services and the larger service importance, the larger node risk. The service importance is obtained by the analytical hierarchy process (AHP). Assume the service set carried on the node is S_i^V , so the node risk model can be formulated as follows:

$$D_i^v = \sum_{s_k \in S_i^V} P_i^v N_i^v I_k, \quad v_i \in p_s(k), S_i^V \subseteq S \tag{1}$$

where D_i^v , P_i^v and N_i^v represent node risk, node failure probability, and node importance, respectively.

In the case of a node failure, all the links connected to it are unavailable. The above node risk model not only can count against the single node failure but also multi-node failures simultaneously.

Edge risk model. Assume service set carried on edges is S_{ij}^E . Likewise, edge risk model is provided as follows:

$$D_{ij}^e = \sum_{s_k \in S_{ij}^E} N_{ij}^e P_{ij}^e I_k \ , \quad e_{ij} \in p_s(k), S_{ij}^E \subseteq S \tag{2}$$

where D_{ij}^e , P_{ij}^e and N_{ij}^e represent the edge risk, edge failure probability, and edge importance, respectively.

Balancing risk of the network. There are still no definite indicators to measure service distribution in the network, and two statistics, variance, and standard deviation are widely used to depict service distribution. Balancing risk of the network is a standard deviation, which is composed of the node and edge balancing risk of the network. The smaller balancing risk of the network, the more uniform service distribution in the network, and vice versa.

In order to derive balancing risk of the network, the average node risk and the average edge risk should be calculated firstly, which are shown as follows:

$$D_{avg}^{V} = \sum\nolimits_{v_i \in p_s(k)} D_i^v / n \tag{3}$$

$$D_{avg}^{E} = \sum\nolimits_{e_{ij} \in p_s(k)} D_{ij}^e / m \tag{4}$$

Thus, balancing risk of the network can be expressed as follows:

$$\begin{aligned} D_{BRS}(P_S) = & \sqrt{\frac{1}{m}\sum\nolimits_{e_{ij}\in p_s(k)} (D_{ij}^e - D_{avg}^E)^2} \\ & + \sqrt{\frac{1}{n}\sum\nolimits_{v_i \in p_s(k)} (D_i^v - D_{avg}^V)^2}, \quad p_s(k) \in P_S \end{aligned} \tag{5}$$

where D_{avg}^{V} and D_{avg}^{E} denote the average node risk, the average edge risk, respectively. $D_{BRS}(P_S)$ represents balancing risk of the network.

Service QoS. Service QoS should be considered as well as the balancing risk of the network during routes planning. We mainly take into account the factors of latency and bandwidth constraints. For simplicity, we ignore the influence of message loss and the bit error rate of services with respect to service QoS.

- *Acceptable latency Constraint.* The end-to-end latency can be represented as the sum of the following items: processing time of all switches, the average queuing forwarding delay, and propagation latency on links in the route $p_s(k)$. The formulation is shown in (6).

$$T_k^p = \frac{1}{c}\sum\nolimits_{s_k \in S} l_{ij} \cdot \eta_{ij}^{kp} + t_1 + r \cdot t_2, \ \ \forall v_i, v_j \in V \tag{6}$$

where T_k^p is the end-to-end latency on route p for s_k. c is a constant denoting signal transmission rate in fibers. l_{ij} is the nodal distance between v_i and v_j. t_1 is the processing time of SDN controller. t_2 is the average queuing forwarding delay. Let η_{ij}^{kp} be a binary decision variable such that:

$$\eta_{ij}^{kp} = \begin{cases} 1 & \text{if the route } p_s(k) \text{ traverses } v_i \textit{ and } v_j \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

r is the number of switches in the route $p_s(k)$, which can be defined as follows:

$$r = \sum\nolimits_{v_i, v_j \in p_s(k)} \eta_{ij}^{kp} \tag{8}$$

Finally, the total end-to-end latency for the whole services can be expressed as follows:

$$T_{total}(P_S) = \sum\nolimits_{p_s(k) \in P_S} T_k^p, \quad s_k \in S \tag{9}$$

- *Link Bandwidth Constraint.* Since different control services have distinct bandwidth requirements (e.g., 64kbit/s, 2Mbit/s, 20Mbit/s), services pass through the same link should satisfy the link capacity constraints. Let $B_{ij}^e(k)$ be the bandwidth requirement of s_k, and ψ is the capacity of link e_{ij}. We use the following constraint.

$$\sum\nolimits_{s_k \in S_{ij}^E} B_{ij}^e(k) \le \psi, \quad e_{ij} \in p_s(k), S_{ij}^E \subseteq S. \tag{10}$$

Dual route intersection Constraint. The primary route and the alternate route are physically independent corresponding to the optimal and the suboptimal route in theory. While the SDN controller fails to plan a fully physically independent dual route for services concurrently in some special network topology, the dual route with the minimal intersection should be planned as well. The dual route intersection represents common elements between the primary and alternate routes except for a source and a destination. $p_s^a(k)$ is the primary route of s_k with the minimal end-to-end latency, $p_s^b(k)$ denotes the alternate route of s_k with the minimum of balancing risk of the network in the premise of latency satisfaction. Λ_k is the dual route intersection degree for s_k, which can be formulated as follows:

$$\Lambda_k = p_s^a(k) \wedge p_s^b(k), \qquad p_s^a(k),\, p_s^b(k) \in P_S . \tag{11}$$

For s_k, to ensure the primary routing separation from the alternate routing as much as possible, the conception of maximal intersection is introduced. It should satisfy the following constraint:

$$\max(\Lambda_k) \le \varphi, \qquad \forall s_k \in S. \tag{12}$$

C. Problem formulation

According to the above analysis, we mathematically formulate the optimization problem minimizing service QoS and balancing risk of the network simultaneously as follows:

Objective Functions:

$$\begin{cases} \min \ T_{total}(P_S) \\ \min \ D_{BRS}(P_S) \end{cases} \tag{13}$$

$$s.t. \begin{cases} 0 < T_k^p \le t_0, & p_s(k) \in P_S & C1 \\ \max(\Lambda_k) \le \varphi, & \forall s_k \in S & C2 \\ \sum\nolimits_{s_k \in S_{ij}^E} B_{ij}^e(k) \le \psi, & e_{ij} \in p_s(k), S_{ij}^E \subseteq S & C3 \end{cases} \tag{14}$$

The objectives in (13) aim at minimizing the total end-to-end delay of all services and balancing risk of the network simultaneously. $C1$-$C3$ in (14) are various constraints to satisfy dual routes planning. And $C1$ is the end-to-end delay constraint in route $p_s(k)$. $C2$ depicts the dual route intersection degree constraint. $C3$ is the service bandwidth constraint. t_0, λ, φ and ψ denote the preset thresholds, respectively.

IV. Risk-Aware Routes Planning Mechanism

Risk-aware routes planning mechanism (RSRM) has been proposed to the constructed system model. The flowchart of RSRM is illustrated in Fig. 2.

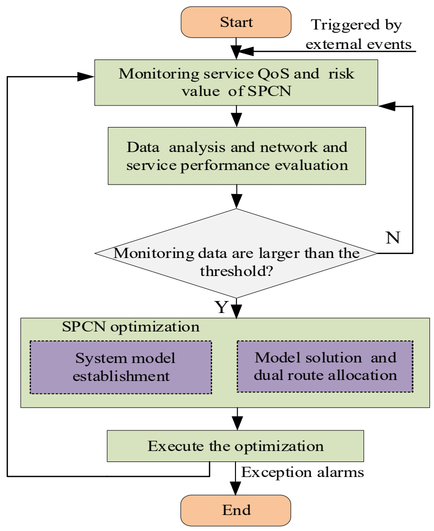


Fig. 2. The flowchart of RSRM.

As shown in Fig. 2, RSRM is triggered by the external events, e.g., fault occurrence, regular inspections and rerouting for services. System model establishment of SPCN oriented to service requirements has been involved in Section III. Next, the system model solution and performance are becoming the key points of RSRM, which will be addressed in Section V and VI, respectively.

V. Model Analysis and Solution

A. System Model Analysis

The above system model based on risk-aware service routes planning is a typical multi-objective optimization, which is proven to be NP-hard [21]. The traditional algorithm e.g., Dijkstra, Floyd, and Bellman-Ford concentrated on the single objective problem cannot solve our system model. We try to solve it on basis of NSGAII (Non-dominated Sorting Genetic Algorithm II).

NSGAII is capable of searching the globally optimal solution of a problem during iterative procedures, which is improved by Deb on basis of NSGA [22,23]. Such algorithm originates from the traditional genetic algorithm, in addition to 'selection', 'crossover' and 'mutation' operations, fast non-dominated sorting, elitist strategy, and the calculation of crowing distance are integrated to improve the algorithm efficiency as well.

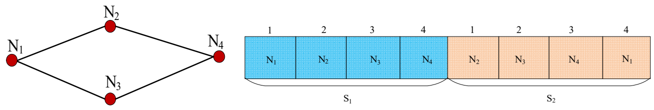
Next, we will describe the basic procedures of NSGAII for RSRM and the procedures are shown in Fig. 4.

B. RSRM

1) Chromosome encoding and decoding

The chromosome encoding and decoding are of significance to the implementation of the algorithm. To improve the efficiency of encoding and decoding, the coding with invariable length integer is exploited. Every chromosome represents a routes planning solution for services. Each service is an independent chromosome segment whose length varies with the number of nodes in the network topology. Each chromosome segment composed of fixed genes which are generated by the random node sequence. The gene location denotes node superiority. All the service segments compose an integrated chromosome. Hence, the individual chromosome length is the product of the number of services and nodes in the network.

As to the decoding, the first node in the routes is the service source node. According to the adjacency matrix of the network topology and gene location in a chromosome, the second node of the service routes can be decoded, and repeat this process until reach the destination node, then a complete routing for all services can be attained. To avoid loops in the routes, next hop of nodes appears only once for each service route.



(a) A simple network (b) Chromosome coding

Fig. 3. A Graphic sample

Suppose there are two services in Fig. 3(a), S_1 (N_1-N_4), S_2 (N_2-N_3) at some network state and a randomly generated chromosome as shown in Fig. 3(b). According to the above method of encoding and decoding, for S_1, the routing is N_1- N_3-N_4 due to the larger gene location index of N_3 than N_2. Similarly, the routing of S_2 is N_2- N_1-N_3.

2) Population Initialization

An appropriate population size is set and the population is randomly generated. Then, the chromosomes not satisfying the bandwidth and latency constraints are removed and we obtain the initial population.

3) Fitness function and non-dominated sorting

As to the multi-objective optimization problem, the traditional genetic algorithm changes multiple objectives with linear relationship into a single objective function by scalarization. However, in our system model, to achieve a smaller total end-to-end latency, services are more likely to converge in the shortest paths, and thus balancing risk of the network are larger. Hence, the two objectives have a competitive relationship with each other. The scalarization process are not suitable for this situation.

The fitness includes the non-dominated levels and the crowding distance for every chromosome according to the value of total end-to-end latency and balancing risk of the network. The operation of fast non-dominated sorting can quickly classify the chromosomes at various levels and obtain the number of non-dominated levels, which makes the excellent chromosomes closer to the Pareto front. To maintain the diversity of the population, the crowding-distance is calculated according to the local distance between the chromosome and the other two adjacent chromosomes of the same level.

4) Selection, crossover, and mutation

The elitism strategy and the tournament are exploited in the 'selection' operation. As to the crossover operation, two parent chromosomes randomly are selected and generates a crossover gene location randomly, and then two offspring chromosomes are bred by exchanging the corresponding genes. The mutation operation selects some chromosomes in terms of mutation probability and interchanges two genes of the service chromosome segment.

The specific procedures are presented as follows.

Step 1: Initialize network topology $G=(V, E)$, service set S and population P_1. Solve route and delete chromosomes not satisfying the bandwidth and the latency constraint. Set g=1 and calculate the objective values.

Step 2: Execute 'selection', 'crossover' and 'mutation' to P_1 and generate a new population N_1.

Step 3: Merge P_g and N_g into R_g. Calculate the objectives and fast non-dominated sorting, crowding distance calculation, Choose the best m chromosomes and generate the population of P_{g+1}. Perform the operations of 'selection', 'crossover' and 'mutation' to P_{g+1} and generate the population of N_{g+1}.

Step 4: If $g<g_{max}$, repeat step 3-4, otherwise, execute step (5).

Step 5: Choose the chromosome with the minimal total end-to-end delay as the primary path planning from the Pareto front.

Step 6: Choose the chromosome with the minimal balancing risk of the network as the alternate route planning from the remaining Pareto front.

Fig 4 provides the details of the algorithm.

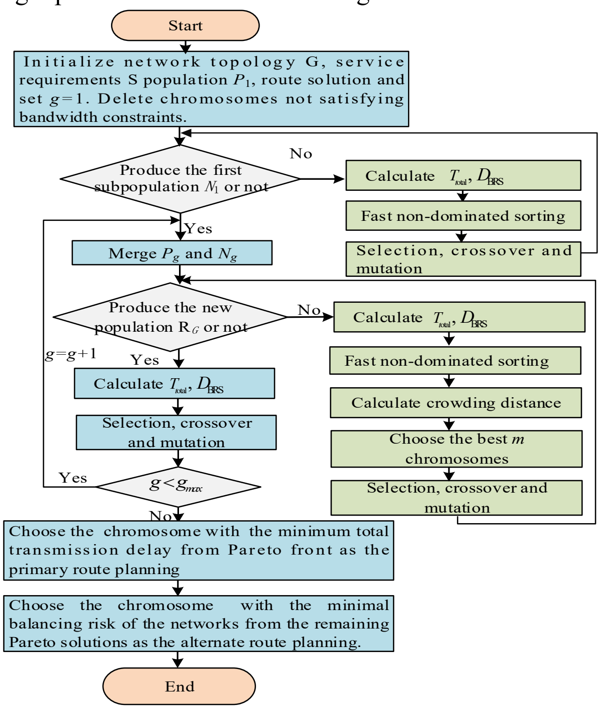


Fig. 4. The procedures diagram of RSRM.

VI. PERFORMANCE EVALUATION

A. Simulation of RSRM

In order to evaluate the performance of RSRM, we select a typical topology deriving from a field communication network of some province in China as shown in Fig. 5 [24]. There are 17 nodes and 25 edges in total. Node16 is the provincial control center and node 15, node 17 are the municipal control centers, respectively. Nodes of 1, 2, 3, 4, 5 are 500kV substations, and the others are 220kV substations. Assume there are 10 control services at some network state and the specific service information is $s_1(3,11,10)$, $s_2(2,7,10)$, $s_3(11,2,10)$, $s_4(11,13,10)$, $s_5(11,6,10)$, $s_6(1,7,10)$, $s_7(6,8,10)$, $s_8(4,9,10)$, $s_9(5,12,10)$, and $s_{10}(11,14,10)$, respectively.

Parameters of the algorithm refer to [8, 25,26]. The end-to-end rate in fibers is $2\times10^5\,km/s$, t_1 is 0.01ms, t_2 is 0.1ms. The population size is 100, the maximum number of iterations is 300, and the mutation probability is 0.1. Our simulations are conducted on MATLAB R2017b.

Fig. 6 provides variations of Pareto front percentage in population versus different evolutional algebra. It can be seen that the average Pareto front percentage remains stable at 34% from the 130th iteration. Due to the minimal total end-to-end delay, the chromosome in the purple rectangle is chosen as the primary route planning. Accordingly, the chromosome in the blue rectangle is selected as the alternate route planning because of the minimum of balancing risk of the network, which can be shown in Fig. 7.

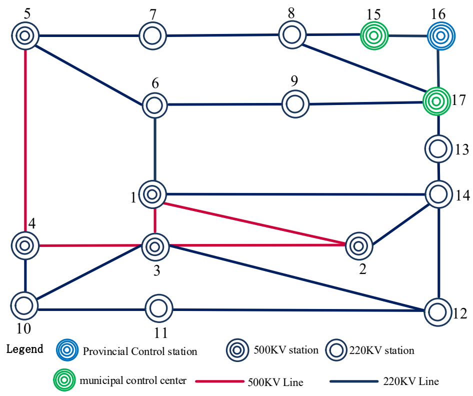


Fig. 5. Communication network topology for SPCN.

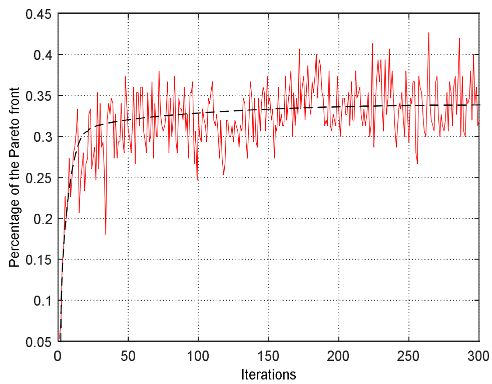


Fig. 6. Pareto front variation with iterations.

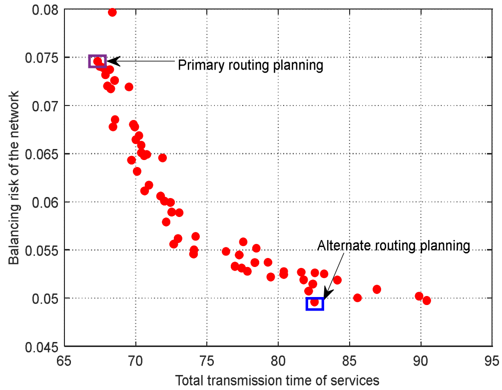


Fig. 7. Distribution of the objectives of chromosomes.

TABLE II. CALCULATIONS OF GA WITH DIFFERENT WEIGHT COMBINATIONS

Index	α	β	T_{total} (ms)	D_{BRS}
1	0	1	100.2000	0.0510
2	0.1	0.9	94.8100	0.0675
3	0.2	0.8	87.785	0.0692
4	0.3	0.7	86.7250	0.0884
5	0.4	0.6	85.4800	0.0899
6	0.5	0.5	84.8550	0.0901
7	0.6	0.4	81.59	0.0964
8	0.7	0.3	80.6800	0.0976
9	0.8	0.2	78.2600	0.0998
10	0.9	0.1	76.3600	0.0942
11	1	0	64.830	0.1080

B. Result Comparison and analysis.

Various classical shortest path algorithms are widely used for Smart Grids [5,12]. To evaluate the performance of RSRM, we compared it with the shortest route strategy based on Dijkstra Algorithm (DA) and Genetic Algorithm (GA).

The parameters configuration in GA are as follows. The population size is 100 and the evolution algebra is 300. Both the selection and the crossover probability are 0.9, respectively. The mutation probability is 0.05. Since there is a striking discrepancy between T_{total} and D_{BRS}, we firstly normalize the two values according to the principle of min-max. Then we convert them into the form of $f = \alpha T_{total} + \beta D_{BRS}$, where f is the objective of GA, α and β are the coefficients of T_{total} and D_{BRS}, respectively. As only one solution could be obtained at a time in GA, we run 10 times with different weight combinations to acquire the near optimization solution.

TABLE II reports specific objectives of different weights in GA. As to this algorithm, the index10 is chosen as the primary route planning due to the minimal total end-to-end delay. Index 3 is selected as the alternate route planning for the minimal intersection and the near minimal balancing risk of the network.

Fig. 8 shows the service-link distribution relationship in primary route planning with different algorithms. It is obvious that the more services carried on the link, the larger risk of the link is. In DA, there are 12 links without services meanwhile there are 3 links with 5 services. That is, there are more unoccupied links which decrease the utilization of network resources. On the other hand, there are fewer critical links carried more services. This is due to that DA concentrates on searching paths with the shortest time delay and causing service aggregation. Correspondingly, the balancing risk of the network is larger which is shown in Fig. 10. Note that the optimum with GA approximates to RSRM while the performance is inferior owing to the subjective choice of weights. As expected, services are more uniformly distributed with RSRM than the other two approaches.

Similarly, service-link distribution relationship with various approaches for alternate route planning are shown in Fig. 9. The results indicate that service distribution with GA is a little better than RSRM. However, there are no obvious differences as both are with the minimal balancing risk of the network.

Fig. 10 shows specific changes about balancing risk of the network for dual route planning. It is obvious that our approach obtains the minimum among the three algorithms. In the primary routes planning, it decreases by 19.95%, 12.77% compared to GA and DA. As to the alternate routes, it reduces by 29.91%, 55% compared to GA and DA, which further demonstrates the effectiveness of this approach. Further, note that balancing risk of the network in primary route planning with different approaches is larger than that of the alternate route planning in total. That is because the primary route planning preferentially guarantees the minimal end-to-end delay requirement, and the alternate route planning focuses on balancing risk of the network as much as possible while meets service QoS.

Fig. 11 demonstrates the total end-to-end delay variation in dual routes. It is noticed that the total end-to-end delay in the primary route planning with RSRM approximates to DA while both are less than that of GA. As the primary route planning with RSRM is chosen from the Pareto front according to the minimal total end-to-end delay. To the alternate routes planning, under the constraint of the minimal intersection, it is prone to allocate services in detour routes, which makes the total delay increase by 20.85% compared to the primary route planning with RSRM. However, the total end-to-end delay with RSRM is still lower than that of GA.

To sum up, as to the primary route planning, the total end-to-end delay with RSRM approximates to DA, while both are lower than that of GA. Balancing risk of the network with RSRM decreases by 30.56% compared to DA, which is the smallest among three approaches. As to the alternate route planning with RSRM, the total end-to-end delay is larger than the primary route planning, however, balancing risk of the network decreases by 14.46%. Compared to GA, it has a smaller total end-to-end delay and balancing risk of the network. Taking S_2 as an example, Fig. 12 provides a specific route of S_2 in an intuitive way with different approaches. We observe that the primary route of S_2 with RSRM is the same as that of DA, and the alternate route of S_2 is the same as that of GA. Therefore, the dual route of S_2 with RSRM can effectively plan a dual route for control services in SPCN

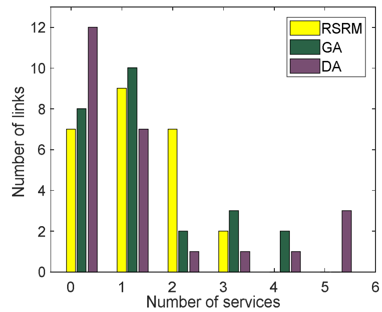


Fig. 8. Services-Links distribution in primary route planning.

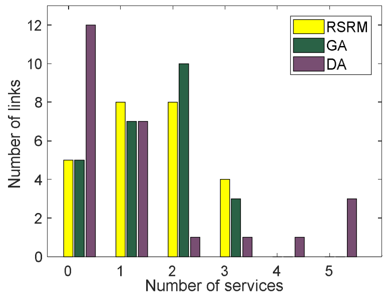


Fig. 9. Services-Links distribution in alternate route planning.

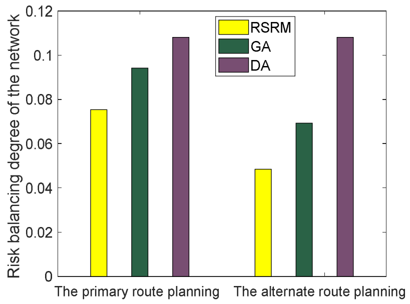


Fig. 10. Balancing risk of the network.

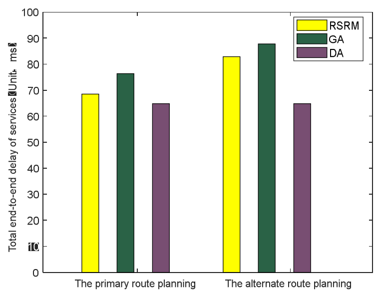
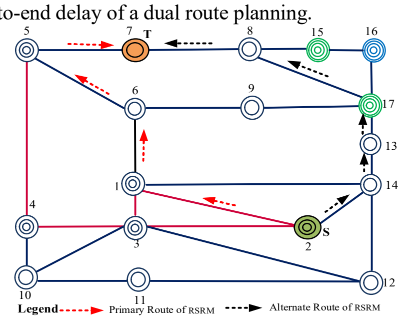
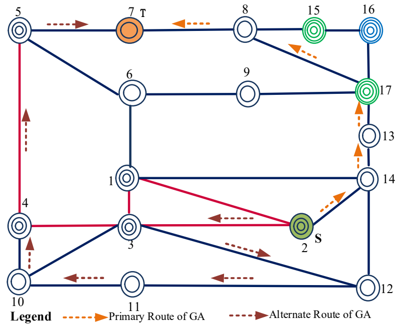


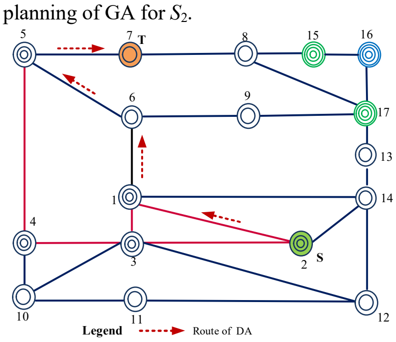
Fig. 11. Total end-to-end delay of a dual route planning.



(a) Dual-routing planning of RSRM for S_2.



(b) Dual-route planning of GA for S_2.



(c) DA route of DA for S_2

Fig. 12. Route planning for service S_2.

VII. Conclusions and Future Work

To ensure stable and coordinative operations of each subsystem in EI, the operator is building a comprehensive defense system, where various control services and panoramic perception services tagged as critical services should be prudently treated to avoid potential failure. Efficient routes planning for these critical services is a practical solution. The mechanism for increasing service dependability and continuous delivery, RSRM has been proposed to implement this scheme. The results demonstrate that control services distribute more uniformly in the network with RSRM than the other two algorithms as well as satisfy service latency demand. As service requirements and network states in EI change frequently, our future work will focus on optimizing the dynamic dual route based on load balancing in consideration of routes optimization as well as network resources allocations in EI.

Acknowledgment

The work is supported by Science and Technology Project from Headquarters of State Grid Corporation of China: “Technical System and Key Technologies Research of System Protection Communication Networks (SGXT0000 ASJS 1700 054)”.

References

[1] K. Wang, X. Hu, and H. Li, “A Survey on Energy Internet Communications for Sustainability,” IEEE Transactions on Sustainable Computing, vol. 2, pp. 231-254, Sep 2017.

[2] Z. Wang, Y. Wang, and X. Qin, “Requirement and Communication Technology of System Protection,” Electric Power Construction, vol. 38, pp. 116-123, May 2017.

[3] L. Liu, Y. Wang, R. Ma, and Y. Sun, “Research on Power System Protection Service Analysis and Communication Bearing Scheme,” Electric Power ICT, vol. 15, pp. 12-18, May 2017.

[4] G Andersson, P Donalek, and R Farmer, “ Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance,” IEEE Transactions on Power Systems, vol. 20, pp. 1922-1928, Nov. 2005.

[5] S.Rinaldi, F. Bonafini, P. Ferrari, and A. Flammini, “Characterization of IP-Based Communication for Smart Grid Using Software-Defined Networking,” IEEE Transactions on Instrumentation and Measurement, vol. 6, pp. 1-10, June 2018.

[6] Y. Hong, D. Kim, and D. Li, “Two new multi-path routing algorithms for fault-tolerant communications in Smart Grid,” Ad Hoc Networks, vol. 22, pp. 3-12, Nov. 2014.

[7] N. Hubin, M. Rifai, and F. Giroire, “ Bringing Energy Aware Routing Closer to Reality with SDN Hybrid Networks,” IEEE Transactions on Green Communications and Networking, vol. 28, pp. 2473-2400, May 2018.

[8] C. Dutra, M. BagaaA, and T. Taleb, “ Ensuring End-to-End QoS Based on Multi-Paths Routing Using SDN Technology,” 2017 IEEE Global Communications Conference (GLOBECOM). Singapore, pp. 1-6, 2017.

[9] T. Matsuura, H. Nakayama, and T. Hayashi, “Fast Detection of Alternative Route under Unknown Failure on SDN Network,” IEEE Global Communications Conference (GLOBECOM). Washington, pp. 1-6, 2016.

[10] B. Cai, Y. Liu, and Y. Ma, “Real-time reliability evaluation methodology based on dynamic Bayesian networks: A case study of a subsea pipe ram BOP system,” ISA Transactions, vol. 58, pp. 595–604, July 2015.

[11] J. Guo, Y. Han, and C. Guo, “Reliability assessment of cyber-physical power system considering monitoring function and control function,” Proceedings of the CSEE, 2016, pp. 2123-2130.

[12] O. Dong, P. Yu, “A Service Routing Reconstruction Approach in Cyber-Physical Power System Based on Risk Balance,” IEEE/IFIP Network Operations and Management Symposium (NOMS) Taipei, pp.1-6, April 2018.

[13] W.Cai, H. Yang, and F.Xiong, “An Optimized Service Routing Allocation Method for Electric Power Communication Network Considering Reliability Power System Technology, vol. 37, pp.3541-3545, Dec. 2013.

[14] Q. Zeng, X. Qiu, and S.Guo, “Risk Balancing Based Routing Mechanism for Power Communications Service,” Journal of Electronics & Information Technology, vol. 35, pp.1318-1324, June 2013.

[15] J. Hu, C. Lin, and P. Zhang, “Performance Evaluation and Optimization of Hierarchical Routing in SDN Control Plane,” Chinese Journal of Electronics. vol. 27, pp. 342-350, Mar. 2018.

[16] Y Jararweh, A Darabseh and M Al-Ayyoub, “Software Defined based smart grid architecture,” Computer Systems and Applications. vol. 14, pp. 243-250 Nov. 2016.

[17] Kim J, Filali F, and Ko Y B, “Trends and Potentials of the Smart Grid Infrastructure: From ICT Sub-System to SDN-Enabled Smart Grid Architecture,” Applied Sciences, vol. 4, pp.706-727, May 2015.

[18] Dong X, Lin H, and Tan R, “Software-Defined Networking for Smart Grid Resilience: Opportunities and Challenges,” Proceedings of the 1st ACM Workshop on Cyber-Physical System Security. New York, pp.61-68, April 2015.

[19] N Dorsch, Kurtz F, and Georg H “Software-defined networking for Smart Grid Communications: Applications, challenges, and advantages,” IEEE International Conference on Smart Grid Communications (SmartGridComm). Italy, pp. 422-427, Nov 2014.

[20] Y. Shi, X.Qiu, and S.Guo, “Optimal planning of optical transmission network using the improved genetic algorithm,” Journal on Communications, vol. 37, pp.116-122, Jan. 2016.

[21] S. Canale, A. Giorgio, and A. Giorgio, “Optimal Planning and Routing in Medium Voltage PowerLine Communications Networks,” IEEE Transactions on Smart Grid, vol. 4, pp. 711-719, June 2013.

[22] K. Deb, A. Pratap, and S. Agarwal, “A fast and elitist multiobjective genetic algorithm,” IEEE Transactions on Evolutionary Computation, vol. 6, pp. 182-197, April 2002.

[23] D. E. Goldberg, “Genetic algorithms in search, optimization and machine learning,” vol. 1, Boston: Addison Wesley publishing company, 1989, pp.79-86.

[24] X. Chen, P. Zhao, P.Yu, and B. Liu, “Risk analysis and optimization for communication end-to-end link interruption in SG cyber-physical system,” International Journal of Distributed Sensor Networks, vol. 14, pp.1-12, Dec. 2017.

[25] P. Zhao, P. Yu, C. Ji, L. Feng, and W. Li, “A routing optimization method based on risk prediction for communication services in Smart Grid,” 2016 12th International Conference on Network and Service Management (CNSM). Montreal, pp. 377-382, 2016.

[26] K. Qin, C. Huang, and C. Wang, “Balanced multiple controllers placement with latency andcapacity bound in software-defined network,” Journal on Communications, vol. 37, pp. 90-103, Nov. 2016.