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An Emerging Survivability Technology for Dispatching Service of Electric Power Communication Network

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ABSTRACT With the rapid development of smart grid and energy Internet, the electric power communication network (EPCN) has more and more data traffic. Under the premise of safety and reliability, this paper studies the survivability technology for dispatching service of EPCN to improve the resource utilization rate of EPCN and increase the network capacity. We design the equipotential preconfigured cycle (*p*-Cycle) algorithms based on the failure independent path-protecting p-Cycle (FIPP *p*-Cycle). To guarantee the optimality of the result, we first build a mixed integer linear program model, namely, equipotential path-limited mixed integer linear program of the FIPP *p*-Cycle. Then, we develop a time-efficient heuristic algorithm, namely, the heuristic algorithm for configuring *p*-Cycle. As an example, we simulate with EPCN topology from the Jiangsu Province of China, considering end-to-end limited-path protection, reliability of demand, and predefined communication topology given by the electrical grid and the presence of a central dispatching center. Compared with the traditional survivability technology, the two proposed algorithms give better performance.

INDEX TERMS Electric power communication network, dispatching service, path protection, survivability technology.

I. INTRODUCTION

To mitigate energy crisis, smart grid [1]–[4] and the advanced version of smart grid (i.e. Energy Internet) [5]–[7] have investigated intensively. Both smart grid and Energy Internet have a strong dependency on information and communication technology (ICT). Especially with the development of Energy Internet, the access of large-scale distributed energy and energy storage systems [6] will have a huge impact on the existing electric power communication network (EPCN).As a key infrastructure of power system, the failure of EPCN will be a threat to the stable operation of the power system and the development of society and economy. Dispatching service means the service of real-time production data transmission among different control centers, power plants and substations in the power system [8], which consist of real-time monitoring service, dispatching operation management service and emergency command system service, such as service of supervisory control and data acquisition (SCADA), energy management System (EMS), security & stability management information system, the protection for management information systems, electric energy metering telemetry system, and so on [9]. More details about dispatching service can be found in [10]. International Electrotechnical Commission (IEC) standards organization developed the IEC 61850 standard to define the allowed power and network equipment, functionalities, inputs/outputs, and all interfaces to EPCN [11]. This paper studies electric power communication network. More details about the construction of EPCN in China can be found in [12].

At present, the survivability technology adopted by EPCN is dual-routing which causes a great waste of the communication pipeline. However, the dispatching service of EPCN has severe requirements for the end-to-end path protection. Due to the fact that the data traffic in EPCN shows distinct traffic patterns and characteristics from the Internet traffic, much more researches are focusing on the traffic modeling [13]–[15], reliability [11], [16] and bandwidth forecasting [17] of EPCN. But as far as we know, none of them tries to explore emerging survivability technology of EPCN. Considering that there are few related researches, this paper designs an emerging protection method for dispatching service of EPCN based on preconfigured cycle (*p*-Cycle).

The main contributions of this paper are summarized as follows: First, equipotential *p*-Cycle generation algorithm is designed with the consideration of length limit for backup path and converging characteristic of EPCN to provide efficient *p*-Cycle based protection. Then, a MILP model is built to configure protection *p*-Cycle in EPCN. Thus it is guaranteed to obtain the optimal solution if possible. In addition, heuristic algorithm is developed to protect the new service in real time and speed up the computing process.

The rest of this paper is organized as follows: Section II analyzes the related work. Section III describes the principle of equipotential *p*-Cycle algorithm, which is divided into three subsections: the equipotential *p*-Cycle generation algorithm (EPG), the MIP algorithm for configuring *p*-Cycle (EpPL-MFIPP) and the heuristic algorithm for configuring *p*-Cycle (EpPL-HFIPP). In section IV, the simulation is implemented based on the actual topology of EPCN and the characteristics of dispatching service, then we analyze the simulation results specifically. Finally, section V summarizes the paper.

II. RELATED WORKS

P-Cycle is an emerging survivability technology in optical networks recently. It is appreciated by researchers due to its mesh-like protective efficiency and ring-like speed in restorable time [18]. According to failure types which are being protected, it can be divided into three types: link protection *p*-Cycle, node protection *p*-Cycle and path protection *p*-Cycle [19]. Among them, Link protection *p*-Cycle and node protection *p*-Cycle can't guarantee end-to-end protection, so we focus on path protection *p*-Cycle. Failure independent path protection (FIPP) *p*-Cycle is a typical path protection *p*-Cycle [20]. Benefiting from the characteristic of pre-cross-connected, FIPP *p*-Cycle can provide reliable path protection for communication service without knowing the location of failure, even without knowing the type of failure. Once the destination node detects the failure, the two end-nodes activate the switching action that directs affected working paths onto the protection paths provided by FIPP *p*-cycles. A FIPP *p*-Cycle can provide one backup path for the on-cycle working path, two backup paths for straddling path, and at least one backup paths for partially on-span and straddling working path.

As shown in FIGURE 1, the blue dotted line A-B-C-D-E-F forms a FIPP *p*-Cycle. B-A-F forms an on-cycle working path d1. If the intermediate node (A) or link (F-A, A-B) fails in path d1, the traffic will be switched to B-C-D-E-F. B-G-F forms a working path d2 that straddles the *p*-Cycle. When an intermediate node (G) or link (B-G, G-F) fails, the traffic of d2 will be switched to B-A-F or B-C-D-E-F. B-C-H-E-F forms a working path d3 partially on-cycle and straddling. When a node (C, H, E) or link (B-C, C-H, H-E, E-F) of path d3 breaks down, the traffic could be switched over to path B-A-F. A-G-H-D-C forms a working path d4 partially on-span and straddling. When an intermediate node (G, H, D) or link (A-G, G-H, H-D, D-C) fails in path d4, the traffic may be switched to path A-B-C.

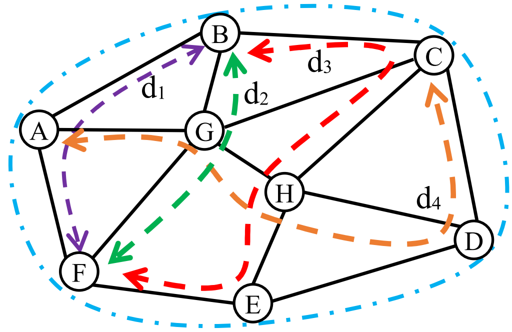

FIGURE 1. Every single work path that FIPP can protect.

So far, we have been discussing about how to perform protection switching action for a single demand when different types of failure occur, but it cannot provide protection for d1, d2, d3 and d4 simultaneously. For example, when node H breaks down, the traffic of d3 will be switched to B-A-F and the traffic of d4 will be switched to A-B-C. The two parties get into conflict in segment A-B. One copy of *p*-Cycle can't carry the traffic of d3 and d4 at the same time. Only disjoint working paths of demands (excluding the source node and the destination node) could be protected by the same *p*-Cycle. As shown in FIGURE 2, the working paths d5, d6, d7, d8 and d9 can be protected by the same FIPP *p*-Cycle A-B-C-D-E-F simultaneously. The specific switching method is similar to the one in FIGURE 1. Like most other researches on survivability, we only consider single node or link failure scenarios, i.e. only single node failure or link failure occurs in the network at the same time, because they are the most frequent types of failure [20].

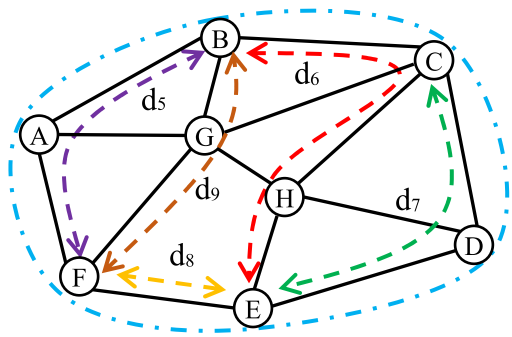

FIGURE 2. Work path sets that FIPP can protect simultaneously.

Currently, research work on *p*-Cycle mainly focuses on the protection of telecommunication networks. First of all, the application of *p*-Cycle to protect elastic optical networks (EONs) has been given prominence in the recent three years. The *p*-Cycle protection technique and the ring coverage technique in elastic optical network are compared in [21], and the benefit of spectrum conversion on the spectrum efficiency is also analyzed. In [22], the problem of realizing spectrum efficient resilience design in elastic optical networks is considered with the application of FIPP *p*-Cycle, and the author designs a *p*-cycle reconfiguration scheme to optimize protection structures on-the-fly. Traffic grooming and spectrum overlap are taken into consideration to design FIPP *p*-Cycle in EON [23]. Spectrum sharing and defragmentation techniques are used to design *p*-Cycle for EON in [24], in which both MILP model and heuristic algorithm are designed. Chen *et al.* [25] optimized FIPP *p*-Cycle in elastic optical networks to realize availability-aware optimization for the first time. Another important aspect of *p*-Cycle protection is the application in WDM networks, which is a traditional topic. In [26], the algorithm based on subgraph partitioning is discussed to control the length of the protection path. Other earlier studies focus on multi-failure [27], dynamic stability of *p*-Cycle [28], *p*-Cycle reconstruction [20] and so on.

In recent years, some researchers have also turned to research on the application of *p*-Cycle in EPCN. The scheme of *p*-Cycle protection for multicast service in EPCN has been sufficiently studied in [29]. Combined with the wiring of power line and EPCN, [31] designs a *p*-Cycle protection algorithm considering shared risk link group (SRLG) in substation communication network. Li *et al.* [30] solves the dynamic *p*-Cycle reconfiguration problem based on service prediction in smart grid optical communication networks. However, they fail to consider the limitation for hops/length and reliability/availability of the protection path in smart grid. Due to dispatching service related to generation and control of power system, the China "Thirteen Five" communications network planning of State Grid Corporation indicates that the number of hops for dispatching services should be strictly controlled to guarantee the quality of service delivery. If we want to apply *p*-Cycle protection method to EPCN, FIPP *p*-Cycle may be better. However, instead of using the FIPP *p*-Cycle, the link protection *p*-Cycle adopted in [26] is closer to the subject of this paper (part 4 will compare the effect of link protection *p*-Cycle). It utilizes graph partitioning approach to control the restored length of the protection path. However, the structure of EPCN is related to the control of power generation and transmission, so we cannot arbitrarily divide it like the Internet. Since dispatching service is mainly convergent service, [26] is not suitable for EPCN. On account of these considerations, this paper designs an emerging survivability technology for dispatching service of EPCN based on the idea of equal potential, which belongs to FIPP *p*-Cycle algorithm.

III. ALGORITHM DESIGN

FIGURE 3 shows the overall flow of the algorithm in this paper. In this section, we first explain the principle of equipotential p-Cycle generation (EPG) algorithm, then we design an MILP model (EpPL-MFIPP) and a heuristic algorithm (EpPL-HFIPP) to configure FIPP *p*-Cycle to EPCN. Limitation of hops and reliability are considered separately

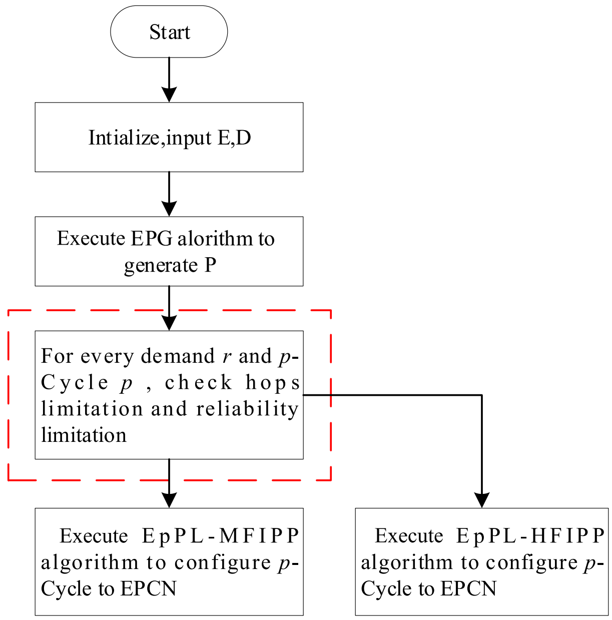

FIGURE 3. The overall framework of the algorithm.

A. EPG ALGORITHM

In order to provide end-to-end path length limited service protection, we first propose an EPG algorithm. When designing *p*-Cycle in a typical communication network that does not consider the limit of protection path, the longer the *p*-Cycle, the more services that a single cycle can protect and the higher the protection efficiency will be. The classical *p*-Cycle generation algorithms (such as Straddling Link Algorithm (SLA) [32], Span-Add(SP-Add) algorithm, Expand algorithm, Grow algorithm [33], and so on.) are based on the idea of expansion and a large number of long *p*-Cycles are obtained. However, considering the limit of the protection path, such *p*-Cycles cannot provide the protection efficiency we need. For example, when the length of a *p*-Cycle is $2L$, there will be a great number of protection path lengths exceeding the limit L. To generate more short *p*-Cycles, we design an equipotential *p*-Cycle generation algorithm, the basic steps are as follows:

1) Utilize single routing algorithm to route all demands, and the path of demand d is R_d;
2) Based on the distance between the source node of every demand and the aggregation center, we assign different potentials g_n to source node n, the potential of the aggregation center is $g_0 = 0$ and the potential of each other node must be a positive integer;

3) Divide all nodes into different equipotential surface F_f. For each equipotential surface F_f, take all the node combinations from it:

$$\{c_{M_f}^n \in C_{M_f} | n = 1, 2, 3 \ldots |C_{M_f}|\}$$

Where M_f is the set of all nodes on the equipotential surface F_f, $C_{M_f} = 2^{M_f}$, which represents the non-null power set of set M_f, $c_{M_f}^n$ represents the n^{th} element of set C_{M_f}, i.e. the n^{th} subset of the set M_f;
As shown in FIGURE 4, with H representing aggregation center (dispatching center), A-C-I-G constitutes the equipotential surface F_1. The potential of each point on the equipotential surface is 1. Meanwhile, B-D-E-F constitutes equipotential surface F_2. The equipotential surface potential of each point is 2:

$$M_1 = \{A, C, I, G\}, \quad M_2 = \{B, D, E, F\}$$

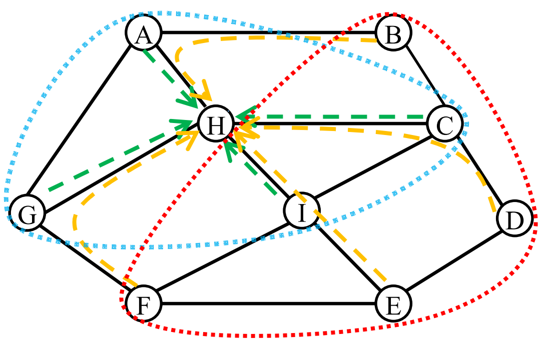

FIGURE 4. **Division of equipotential surface.**

4) The Equipotential P-cycle Generation algorithm (EPG) is used to connect the aggregation center nodes and the nodes in set $c_{M_f}^n$ to form a minimum p-Cycle and traverses all of it.

The problem solved in step (4) is similar to the traveling salesman problem (TSP), which is a typical NP-hard problem. So we design a heuristic algorithm to generate p-Cycle from the equipotential surface.

The basic idea of EPG algorithm is: Start from a node, find the shortest path between it and the unmarked node sets Q. Add the nodes of the shortest path to the p-Cycle sets in sequence. For nodes that have already been used, they are immediately deleted from the unmarked node set, and all the edges connected with them are deleted at the same time to avoid any nodes or links being reused, which may lead to non-simple p-Cycle or non-cycle structure. It is repeated until all the nodes of Q are marked. Then all the nodes in the set of p-Cycle nodes form a p-Cycle in order.

Q represents for sets that composed of $c_{M_f}^n$ and convergence center, and $P(Q)$ represents for the smallest p-Cycle made up of all the nodes in set Q. The given pseudocode illustrates the algorithm further.

Algorithm 1 EPG Algorithm

Input : $G(V, E)$, Q
Output: $P(Q)$
for $\forall q_i \in Q$ do
  $Q = Q - q_i$
  find min {distance (q_i to Q)}$= d_{ij}$, path r_{ij}
  delete q_j from Q
  while $Q \neq \emptyset$
    find min{ distance(q_i to Q)}$= d_{ia}$,
    find min{ distance(q_j to Q)}$= d_{jb}$,
    path(q_i to q_a) $= r_{ia}$, path(q_j to q_b) $= r_{jb}$;
    if $d_{ia} \neq d_{jb}$ then
      $d_{km} \leftarrow \min\{d_{ia}, d_{jb}\}$, path($q_k$ to q_m)$= r_{km}$
      for $\forall q_n \in r_{km}$, $(q_n \neq q_m)$ do
        delete any span associated with q_n from G
        delete q_n from Q, $q_k \leftarrow q_m$
    else if $q_a = q_b$ then
      for $\forall q_n \in r_{ia}$, $(q_n \neq q_a)$ do
        delete any span associated with q_n from G
        delete q_n from Q, $q_i \leftarrow q_a$
    else
      for $\forall q_n \in (r_{ia} \cup r_{jb})$, $(q_n \neq q_a, q_n \neq q_b)$ do
        delete any span associated with q_n from G
        $q_i \leftarrow q_a$, $q_j \leftarrow q_b$, delete q_n from Q
  find min{distance(q_i to q_j)} $= d_{ij}$, path (q_i to q_j) $= r_{ij}$
  combine all r to cycle(i)
$P(Q)$ ←min{length(cycle(i))}

B. EpPL-MFIPP ALGORITHM

Based on EPG algorithm, we configure the p-Cycle set generated by EPG into the network to protect all demands, and the p-Cycle is configured using a mixed integer linear programming model (MILP), and the symbols of this algorithm are shown in Table 1. Before the MILP model, we need to calculate some key parameters.

To meet the requirement of smart grid, we have another two limitations to consider. First, the hops of working path and backup path should be no more than 6, according to data network technical specification of China [12]. We call this hops limitation; Second, the reliability of EPCN should meet the requirements of five to six 9's [11]. we call it reliability limitation.

$$hp_r \leq L \tag{1}$$

For hops limitation, the parameter α_r^j is designed after the generation of candidate p-Cycle sets. We check the path limited protection capability of p-Cycle j, which can provide for demand r. Even p-Cycle j can provide 2 protection paths for demand r, α_r^j could equals 0 in the worst case, because we do care the hops of protection path. We don't limit the protection path when generating p-Cycles, because even if

TABLE 1. Variables in EpPL-MFIPP

Parameters	Meaning
E	Span sets of graph, indexed by i
D	Demand sets, indexed by r
P	P-Cycle sets, generated by EPG, indexed by j
A_r	Availability of demand r
θ	Availability of optical fiber per kilometer
ξ	Availability of substation and EPCN
hw_r	The hops of working path for demand r
dp_r	The distance of protection path for demand r
hp_r	The hops of protection path for demand r
Δ	A large integer constant, (Typical value:10000)
∇	A small constant, (Typical value:0.0001)
c_i	Cost of the i^{th} link (Typical value:1)
n_r	Number of demand r
α_r^j	Number of protection paths that p-Cycle j can provide for demand r with length limited to L, calculated in advance (Typical value :0,1,2)
γ_r^j	Number of protection paths that p-Cycle j can provide for demand r, with the consideration of hops limit and reliability limit. (typical value:0,1,2)
x_i^j	If span i is on cycle span of p-Cycle j ,1 for yes and 0 for no (Typical value:0,1)
$\delta_{u,v}$	If demand u and demand v can be protected by the same p-Cycle , 1 for yes and 0 for no (Typical value:0,1)
Decision variables	**Meaning**
e_i	Copies of backup capacity installed on span i
n^j	Number of p-Cycle j is placed to network
n_r^j	Number of p-Cycle j is used to protect demand r
β_r^j	If p-Cycle j is used to protect demand r ,yes by1,no by 0 (Typical value:0,1)

the length of p-Cycle j is greater than L and no more than $2L$, it may provide 1 or more protection paths that meet the requirement for demand r in some cases. In extreme cases, α_r^j could equals 2 in the best case when demand r straddle p-Cycle j in half splitting. It does help improve resource utilization. We neither limit the protection path in MILP model, because it will introduce a large number of variables and constraints, and the cost is much higher than the benefit.

For the reliability limitation, reliability of EPCN is usually discussed in terms of 2-terminal, k-terminal, or all-terminal reliability [11]. In this paper, we consider 2-terminal reliability for every demand r. And equation (2) gives the reliability of demand r. If the working path and protection path of demand r fails, we think it's unreliable. Here we consider both optical fiber failure and substation failure, since our FIPP p-Cycle can provide both link failure and node failure protection (if the source and destination of demand works well).

$$A_r = 1 - \left(1 - \theta^{dw_r} \cdot \xi^{hw_r}\right) \cdot (1 - \theta^{dp_r} \cdot \xi^{hp_r}) \tag{2}$$

Where θ represents the optical fiber reliability per kilometer. Using common parameters as the Mean Time Between Failures (MTBF, i.e. the expected time between two failures of the component) and the Mean Time To Repair (MTTR, time required to repair or replace the component): θ = (MTBF-MTTR)/$MTBF$ [34]. In Paper [11], measures has been promoted to improve the substation reliability to five 9's, so in this paper we suppose that reliability of substation is $\xi = 0.99999$, and we require the reliability of demand r is no less than ξ: $A_r \geq \xi$. Obviously this is a no-linear constraint. We must make it linear. So we deduced the following formula from equation (2) and $A_r \geq \xi$.

$$\zeta^{dp_r} + hp_r \leq \log_\xi \frac{\xi - \theta^{dw_r} * \xi^{hw_r}}{1 - \theta^{dw_r} * \xi^{hw_r}}, \quad \zeta = \log_\xi \theta \tag{3}$$

From this formula, we can see the reliability limitation is guaranteed through distance and hops of protection path, which is consistent with hops limitation. These two limitations are associated closely, so we don't consider the two limitations separately. We design a checking procedure considering the two limitations simultaneously to calculate the key parameter γ_r^j for MILP model. As shown in FIGURE 5.

We call this MILP model Equipotential Path Limited-Mixed Integer Linear Programming Failure Independent Path p-Cycle algorithm (EpPL-MFIPP). And the specific model is shown below:

$$\text{Objective: } \min \left\{ \sum_{\forall i \in E} c_i \cdot e_i \right\}$$

$$\text{Constraints: } \sum_{\forall j \in P} \gamma_r^j \cdot n_r^j \geq n_r, \quad \forall r \in D \tag{4}$$

$$\delta_{u,v} + 1 \geq \beta_u^j + \beta_v^j$$

$$\forall u \in D, \quad \forall v \in D, \ u \neq v, \ \forall j \in P \tag{5}$$

$$\beta_r^j \geq \nabla \cdot n_r^j, \quad \forall r \in D, \ \forall j \in P \tag{6}$$

$$\beta_r^j \leq \Delta \cdot n_r^j, \quad \forall r \in D, \ \forall j \in P \tag{7}$$

$$n^j \geq n_r^j, \quad \forall r \in D \tag{8}$$

$$e_i \geq \sum_{\forall j \in P} n^j \cdot x_i^j, \quad \forall i \in E \tag{9}$$

The model is dedicated to providing 100% protection for demands in the network with minimal protection cost. So the objective function (4) is used to minimize the total cost. Constraint(4) guarantees the sufficient backup capacity to protect 100% single link or node failure. Only disjoint demands could be protected by the same p-Cycle, which is realized by constraint (5). Constraints(6) and (7) pass compatibility condition (constraint(5)) to constraint(4). They guarantee that $n_r^j > 0, \beta_r^j = 1, n_r^j = 0, \beta_r^j = 0$. Constraint (8) indicates that the number of p-Cycles is determined by every demand. Constraint (9) ensures that the backup capacity configured on each link is no less than the total capacity of the link used by all p-Cycles.

C. EpPL-HFIPP ALGORITHM

In order to reduce the difficulty of solving the MILP model, we design an Equipotential Path Limited-Heuristic FIPP

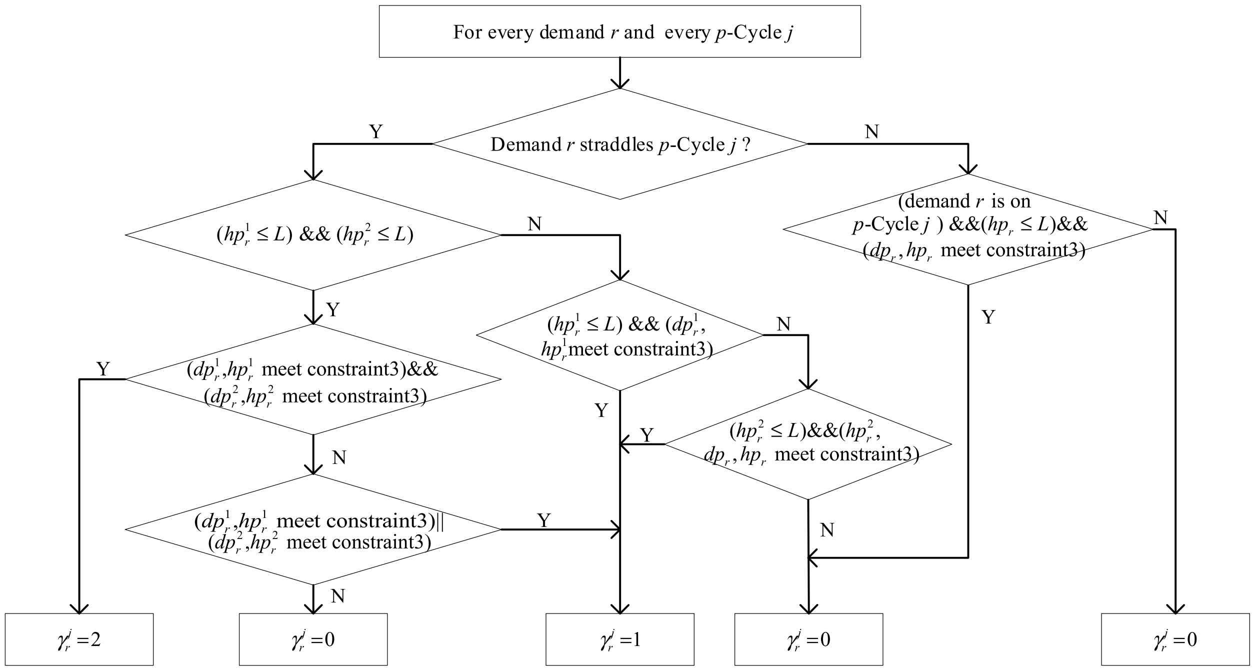

FIGURE 5. **Constraint check for hops and distance of protection path.**

p-Cycle algorithm (EpPL-HFIPP) based on EPG. Utilizing pure heuristic algorithm to configure p-Cycle generated by EPG, the main challenge is to guarantee the non-intersection of working paths for different demands, corresponding to the constraint(5) in the EpPL-MFIPP algorithm. To guarantee the non-intersecting working paths, we have two solutions [35]: The first one is that we can find all the disjoint sets of paths in the network, and then construct p-Cycles according to the disjoint sets of paths. Finally, we can use the conventional p-Cycle configuration algorithm. The other one is that we can find disjoint working path sets from candidate p-Cycles according to the existing demand matrix, and then find the "efficient" p-Cycle to configure.

It seems that the first solution may have a better performance, but in fact, supposing the network has N nodes, there will be $N(N-1)$ node pairs. If there is only one path between the two nodes in a pair, then there will be $M = N(N-1)/2$ paths in the whole network. There may be $A_M^n = M \cdot (M-1)\cdots(M-n+1)$ sets of disjoint working paths with n paths. For each set, we need to repeat the test about whether path is disjoint $n(n-1)/2$ times, then the total number of test will be $\sum_{n=1}^{M} A_M^n \cdot n(n-1)/2$. Obviously, it's NP-hard. When the size of network is large, it is infeasible to get the results. The second solution may be more feasible, so we design EpPL-HFIPP algorithm based on it. In addition, we will give a pseudo-code to describe more details of the EpPL-HFIPP algorithm.

Table 2 shows the meaning of the relevant variables in the pseudo-code. Here we require that the p-Cycle can provide the demand with a protection path length no more than L.

Algorithm 2 EpPL-HFIPP Algorithm

Input : $W, G(V, E), D, P$
Output: P'
1 **for** *each* W_j, **do**
2 **for** $\forall w_r \in W_j$, **do**
3 **new**$S_{j,r}$, $S_{j,r} \leftarrow \{w_r\}$, $W_j' \leftarrow (W_j - w_r)$
4 **while** $W_j' \neq \emptyset$
5 randomly choose w_k from W_j'
6 and delete it from W_j'
7 **if** *w_k compatible with $S_{j,r}$*
8 add w_k to $S_{j,r}$
9 repeat it N times ($N = length(W_j)$)
10 delete repeated $S_{j,r}$
11 $U \leftarrow D$
12 **while** $U \neq \emptyset$
13 **for** *each* $S_{j,r}$, **do**
14 $S_{j,r}' \leftarrow (S_{j,r} \cap U)$
15 find the most efficiency $S_{j,r}'$
16 delete $S_{j,r}'$ from U, add $P(j)$ to P'

In the pseudo-code, line 5 introduces randomness, no matter whether it is sequential, reverse or random, there is no guarantee that all the disjoint sets of demand can be protected by p-Cycle j. Therefore we repeat it (lines 2∼8) N times to get the disjoint demand sets that can be protected by p-Cycle j as many as possible. Then we delete the repeated ones to reduce calculation complexity.

TABLE 2. Variables in EpPL-HFIPP.

Variable	Meaning
w_r	Demand r
P'	The set of p-Cycles configured to protect all demands
N	The number of repetitions
W_j	The demand sets that p-Cycle j can protect (fixed)
W_j'	A copy of W_j (changeable)
$S_{j,r}$	The r^{th} compatible demand sets that p-Cycle j can protect
$S'_{j,r}$	The r^{th} compatible demand sets that p-Cycle j can protect (real time)
U	Currently unprotected demand set

IV. PERFORMANCE EVALUATIONS

In order to validate the effectiveness of the proposed algorithms, this paper uses a sample EPCN topology (shown in FIGURE 6) from Jiangsu Province of China as a simulation graph and three kinds of comparison algorithms are adopted. Cables for EPCN of Jiangsu Province are mainly composed of Optical Fiber Composite Overhead Ground Wire (OPGW) and All-Dielectric Self-Supporting optical fiber (ADSS), which belong to aerial fiber. So we can get parameters for reliability of optical fiber from TABLE 1 in [35].

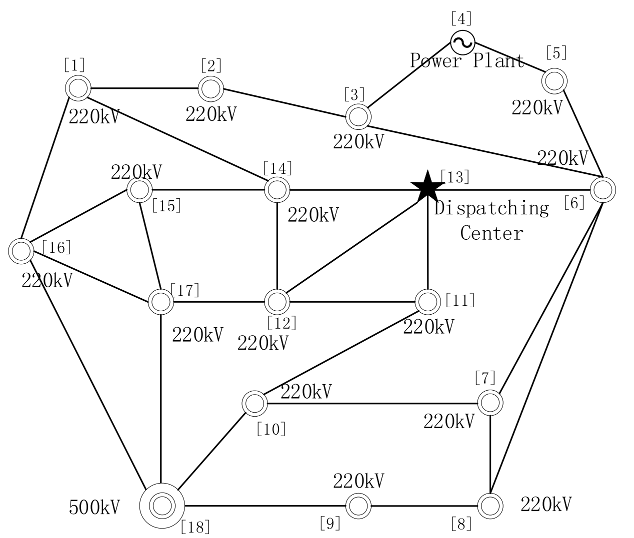

FIGURE 6. Sample of EPCN from Jiangsu province in China.

The first comparison algorithm is dual routing algorithm, which is used by EPCN at current (using the Dijkstra algorithm to calculate two paths for each service and we guarantee that the two routings are disjoint in terms of nodes and links). We call it dual routing without p-Cycle (DR-WPC). The second comparison algorithm is the basic algorithm of literature [36] (link protection p-Cycle algorithm without cycle enumeration) which can date back to [37]. In consideration of fairness, we add the hops limitation of p-Cycle to the constraints. We call this algorithm without candidate cycle enumeration - mixed integer linear program link p-Cycle (WcCE-MLPC) and the hops of p-Cycle is limited to 7 (it equals to $L \leq 6$). We need to explain that we don't add reliability limitation for this algorithm, it's infeasible. The third comparison algorithm is the basic algorithm of [22] and we add hops limitation and reliability limitation to the constraint. We call it path limited-mixed integer linear program failure independent path p-Cycle (PL-MFIPP). Similarly, the path limits L of other algorithms in this paper are all set to 6 as well. According to Data Network Technical Specification of China Southern Grid [12], direct routes of city and county-level dispatching data network cannot exceed 6. In the simulation of demand generation, every source node (220kV substation) converges to the dispatching center and a higher level substation (500kV substation) according to a typical convergence demand generation mode of EPCN. At the same time, in addition to the dual routing algorithm used as a comparison algorithm, each of the other comparison algorithms consists of single-routing algorithm and a protection algorithm (such as PL-MFIPP). To solve the MILP model, we use the solver Gurobi Optimizer 7.5 from Google, and the default value for gap is 0.0001. During the simulation, the generation and protection of the demands are all performed based on the VC-4 channel. Demand concurrent number (DCN) refers to the number of demands started from the source node to the destination node at the same time.

The redundancy of several protection algorithms is compared in FIGURE 7. When we talk about redundancy, we consider it as the ratio of the cost of protection path to the cost of working path. Obviously, it can be seen that DR-WPC algorithm has the highest resource redundancy of 1.4824. The EpPL-MFIPP algorithm has the lowest redundancy in this paper, and the redundancy during the simulation is always below 1.1. The EpPL-HFIPP algorithm proposed in this paper has second least redundancy, followed by the traditional PL-MFIPP algorithm. As the demand concurrent number increases, redundancy gradually decreases and

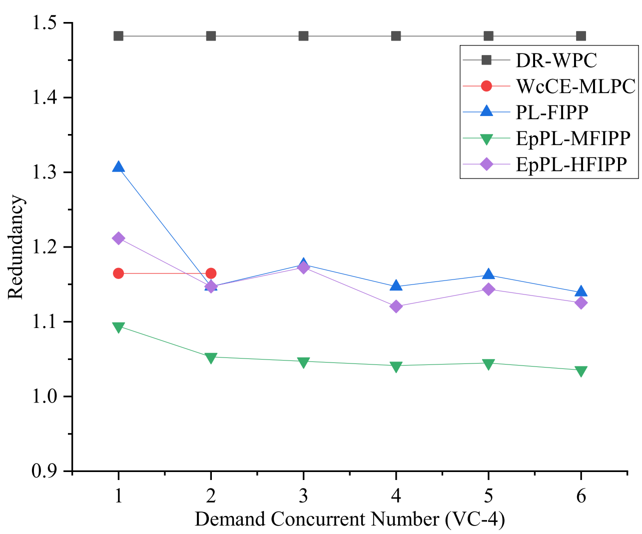

FIGURE 7. Redundancy comparison of different protection algorithms.

tends to be stable. It should be noted that the WcCE-MLPC algorithm does not complete the calculation, because it takes a desktop computer equipped with 4GB RAM and Core i5 processor more than 24 hours to get an infeasible solution when the demand concurrent number is 3. And according to the calculation results when the demand concurrent number is 1 and 2, WcCE-MLPC algorithm is mediocre. In addition, WcCE-MLPC can be considered as one of the most efficient link protection *p*-Cycle algorithms so far. Therefore, the simulation result shows that the link protection *p*-Cycle is less effective in end-to-end protection scenario. Considering that it cannot provide node protection or reliability guarantee, all FIPP algorithms and DR-WPC algorithm works well in the same cases. In summary, the link protection *p*-Cycle is not a good protection scheme for EPCN of Jiangsu Province. That's why we don't recommend link protection *p*-Cycle which is used in [26].

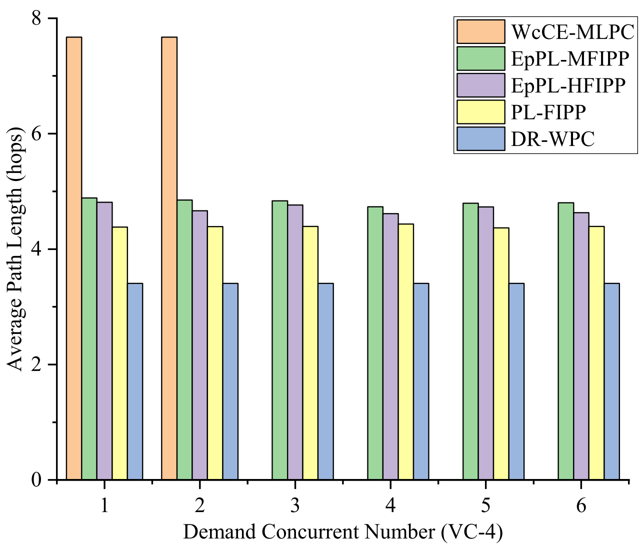

FIGURE 8. Comparison of average protection path lengths for different algorithms.

FIGURE 8 compares the average protection path length of several algorithms. There is no doubt that the average protection path of DR-WPC is the shortest, but its redundancy is quite high. So, this paper considers emerging protection algorithm like *p*-Cycle protection algorithm to replace it. And we can see that even the length of link protection *p*-Cycle is limited to 7, WCCE-MLPC algorithm is still unable to provide the protection path we expected. The reason is that link protection *p*-Cycle algorithm can protect only one hop of a working path. When a link fails, the traffic on the link is switched over the link protection *p*-Cycle. Adding the non-fault link on the original working path and the protection path of the failed link, we will get an actual protection path, which is almost 8 hops. In addition, for the reasons given above, no simulation results are obtained when the demand concurrent number exceeds 2. However, the average protection path lengths of EpPL-MFIPP, EpPL-HFIPP and PL-MFIPP are close enough to meet the requirements. We can get another conclusion from FIGURE 7: Excluding WcCE-MLPC, the higher the resource redundancy, the longer the length of the protection path. EpPL-MFIPP and EpPL-HFIPP have made some concessions in hops limitation to improve resource utilization.

TABLE 3 gives a more visible comparison for different survivability algorithms in terms of average redundancy and average path length of protection path. Under the condition that the length of the protection path satisfies the requirement, the EpPL-MFIPP algorithm in this paper achieves the best performance, followed by the EpPL-HFIPP algorithm in this paper.

TABLE 3. Comprehensive comparison of different algorithms.

Algorithm	DR-WPC	WcCE-MLPC	PL-FIPP	EpPL-MFIPP	EpPL-HFIPP
Average redundancy	1.4824	1.1647	1.1797	1.0526	1.1383
Average length	3.4054	7.6710	4.3937	4.8168	4.7023

FIGURE 9 counts the number of *p*-Cycles used by different algorithms. We can see that the EpPL-MFIPP algorithm designed in this paper has the least number of *p*-Cycles. The numbers of *p*-Cycle used by PL-MFIPP and EpPL-HFIPP algorithms in this paper are comparable. However, the EpPL-HFIPP algorithm in this paper belongs to the pure heuristic algorithm which can protect new demand on the fly and only need a short time, while the PL-MFIPP takes a long time to calculate the result. What's more, the EpPL-HFIPP algorithm can configure protection *p*-Cycle to protect the new generated demand separately, but PL-MFIPP must calculate the protection *p*-Cycles for all demands. The WcCE-MLPC algorithm takes the longest time, and the maximum number of *p*-Cycles is required.

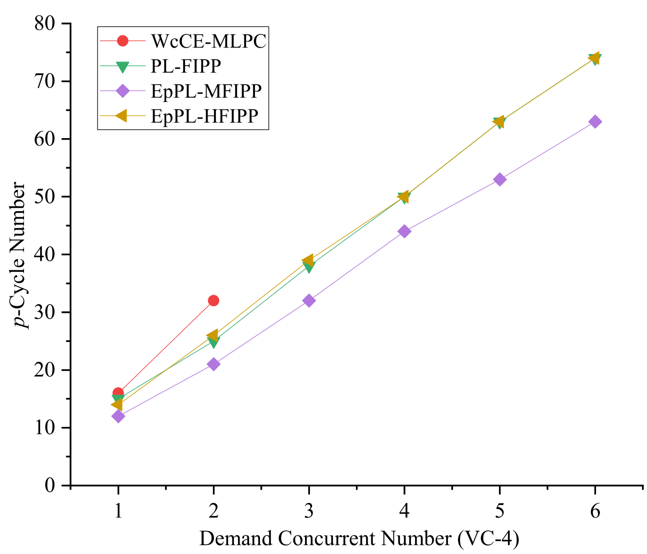

FIGURE 9. Comparisons of the number of *p*-Cycles for different algorithms.

Similarly, for reasons stated above, the WcCE-MLPC simulation results are not given when the demand concurrent number is greater than 2.

To verify the reliability of algorithms in this paper, we analyze EpPL-MFIPP and EpPL-HFIPP under different DCNs. For every DCN, we count the average reliability of every demand r in FIGURE 10. If some demands have the same source node or destination node, but different protection schemes, we treat them as the same demand and average the reliability of different protection schemes. We find that the reliability of different demands fluctuates between five 9's and six 9's. Reliability of very few demand even exceed six 9's. Generally speaking, DCN does not have a significant impact on demand reliability. EpPL-HFIPP has slightly better reliability than EpPL-MFIP in meeting the reliability requirements.

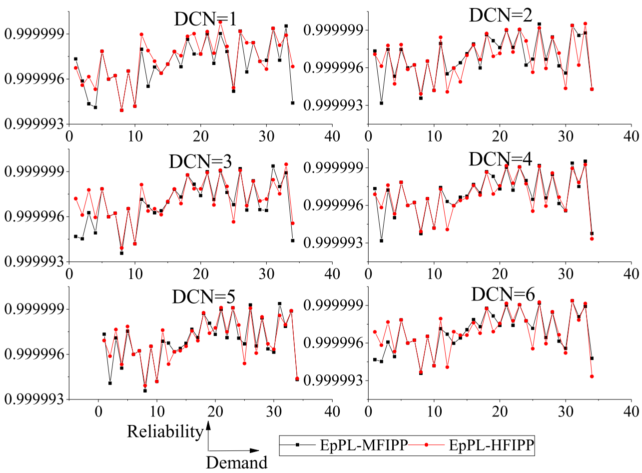

FIGURE 10. Reliability of demand for different DCNs.

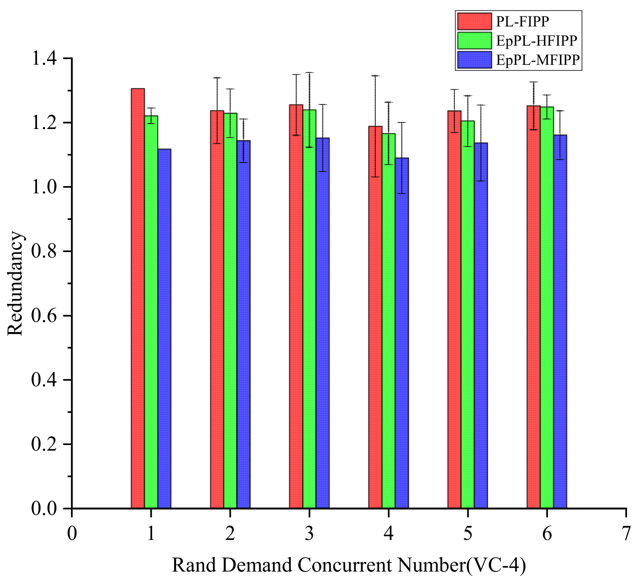

FIGURE 11. Redundancy comparison of different algorithms considering demand randomness.

The horizontal axis represents for the maximum number of demand random concurrent. For each number, we run the algorithm 5 times and count its redundancy respectively, and finally we get the error bars shown in FIGURE 11. We can see that the EpPL-MFIPP algorithm shows the best redundancy when the maximum demand concurrent number changes, followed by the EpPL-HFIPP algorithm and the worst one is the PL-MFIPP algorithm. There is no significant difference in terms of the robustness among the three algorithms. However, when the demand concurrent number is 1, there is no change in the redundancy of EpPL-MFIPP and PL-MFIPP algorithms. Only the redundancy of the EpPL-HFIPP shows minor fluctuations, because the heuristic algorithm is less stable than the optimization algorithm.

V. CONCLUSION

In this paper, we focus on an emerging survivability technology for dispatching service of EPCN. We take full account of the operational characteristics of smart grid in China: end-to-end limited path protection, reliability of demand, predefined communication topology given by the electrical grid and the presence of a central dispatching center. Based on the FIPP algorithm, we design the MILP method EpPL-MFIPP and pure heuristic algorithm EpPL-HFIPP for configuring p-Cycle in EPCN. In more than 30 random concurrency tests, compared with the dual routing algorithm currently used by the EPCN, the redundancy of the EpPL-MFIPP algorithm is reduced by 25.58% on average, and the redundancy of the EpPL-HFIPP algorithm is reduced by 18.19%. Compared with the traditional FIPP algorithm, the redundancy of EpPL-MFIPP algorithm is reduced by 11.54% on average, and the redundancy of EpPL-HFIPP algorithm is reduced by 2.74% on average.

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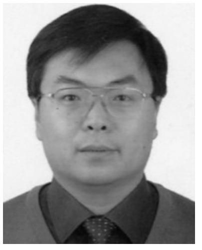

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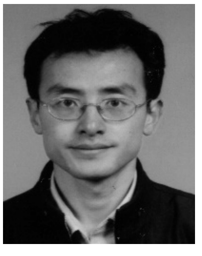

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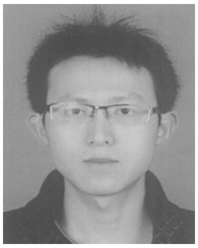

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