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Reliable Remote Relay Protection in Smart Grid

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Abstract

As the false trips of remote protection relays are among the main reasons behind cascading blackouts, it is critical to design reliable relay protection. Even though common protection schemes on traditional power systems have been investigated for a few decades, cascading failures in recent years indicate more research needed in this area. Consequently, researchers have proposed agent-based methods on the Smart Grid (SG) to address this issue. However, these existing agent-based methods simply use TCP protocol without considering real-time communication requirements (such as bandwidth and delay). To deal with this issue, several methods for efficient network resource management are proposed. Furthermore, these existing methods do not consider the potential issues in practical communication networks, which may result in delay violation and trigger relay false trips. We have discussed simple backup solutions in the previous work. In this paper, in addition to network efficiency, we focus on improving the system reliability by exploring known power system information and minimizing the chances of false trips of important remote relays, e.g., defining power line priorities based on their importance. Moreover, to further improve the system reliability, we also investigate the peer-to-peer protection approaches to address the single point of failure of centralized control center.

Keywords

zone 3 relay; cascading failure; real-time communications; smart grid protection; power-aware resource management

1 Introduction

To deal with device failures, prevent damages to power sys-tem components, and avoid broad-spread disturbances, modern power transmission systems use different types of local and remote relays to isolate such issues and stop disturbances from spreading. In the protection system, directional relays (especially remote zone 3 relays) are critical in protecting transmission lines as backup protection, and they are universally deployed in protection systems [1], [2]. However, some over-sensitive remote relays may trip due to various reasons and generated cascading failures in recent large scale blackouts [3], [4]. While researchers have developed many methods to prevent such failures on the traditional power systems [5]–[7], these existing methods failed to solve the problem and could not stop the spread of cascading failures due to the false trips of remote relays. We will focus on this critical issue in this paper.

In the emerging Smart Grid (SG), many intelligent devices are employed to monitor and control power system components, which allow us to achieve more effective protection for dealing with the false trips of remote relays. These de-vices communicate with power control systems on real-time networks, provide instant system status, and conduct precise control. In this research direction, agent-based protection systems [8], [9] have been designed to utilize SG real-time communications to prevent the false trips of remote relays. However, the existing methods simply use TCP/UDP transport protocols to deliver monitor and control messages without band-width and delay guarantees, and simply assumed ideal dedicated communication network paths; they did not address practical network issues due to many potential errors such as simple traffic congestion, routers/links errors/misconfigurations, or malicious attacks that cause bandwidth and delay violation on communication paths. Meanwhile, more and more SG applications and services are being developed for reliability, efficiency, and system protection [10]–[13]. Many of these applications require high bandwidth and short latency (e.g., emerging PMU operations [12]), and may cause temporary congestion (e.g., in a diagnostic mode). Therefore, we cannot simply assume a dedicated network for each application and have to carefully manage real-time communication network resources to support the operations of these applications.

The previously-proposed agent-based schemes assume ideal dedicated network paths between protection relays and their master agent for real-time monitoring and control [8], [9], without considering the details of network resource management and potential link errors. To fill this gap, our previous work focused on methods for basic network resource management for ensuring bandwidth and delay guarantees. We also designed a

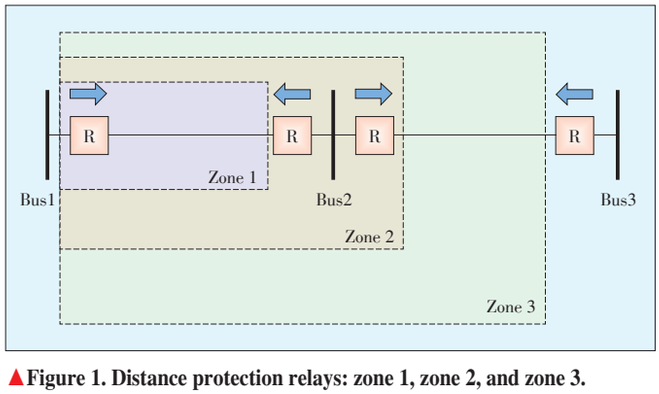
simple backup method presented in [14].

In this paper, in addition to address network management, we focus on system reliability, because the reliability of power system become extremely critical and today's information-focused world is highly dependent on the availability of power systems. To enhance the system reliability of agent-based solutions, we will first introduce a master-based static reservation scheme for delay and bandwidth guarantees, and then discuss different backup methods to address potential communication errors in practical networks. We further propose a power-ware protection approach by exploiting known information about power systems in order to define power line priorities based on their importance. Furthermore, as the master-based solution is highly dependent on the availability of the master agent, to address this issue, we further present a Peer-to-Peer (P2P) based scheme as an alternative to the master-based scheme to address the single point of failure of centralized control center. Although the path failures are low probability events, when they occur, they do cause serious issues in remote relay protection schemes and damage the entire power system. The proposed ideas in this paper are not limited to only relay protections and can be employed for many other real-time control and monitoring systems.

We organize the remainder of this paper as follows. In Section 2, we will discuss related work. In Section 3, we will present the enhanced primary path construction method, different backup methods, and the proposed power-ware scheme. In Section 4, we will focus on the proposed P2P-based scheme. In Section 5, we will evaluate the proposed solutions and discuss their pros and cons. In Section 6, we will summarize this work and elaborate our future research in this direction.

2 Related Work

Distance protection relays are one of the most common relays used for power transmission lines [1]. The operation of a distance relay is determined by the impedance measured by the relay, which is used to estimate the distance from the relay to a fault. We usually have three protection zones as shown in **Fig. 1** [9]. Protection zone 1 is the basic protection of a distance relay, which covers about 80% of the length of a transmission line. The protection zone 2 covers a little more than zone 1, usually about 120% of the length of a transmission line. Protection zone 3 covers the first transmission line and also about 80% of the second line. We can adjust the relay settings for zone 1, zone 2, and zone 3 protection, and construct both primary protection and backup protection with different delays. Normally, we use zone 1 as the primary protection, which is almost immediately triggered when a fault is detected, e.g., with a delay of a few milliseconds. We use zone 2 and zone 3 protection as backup mechanisms, which are triggered after given tripping delays when a fault is detected. These tripping delays are often determined by the protection distance, e.g., a zone 2 protection may waits for 0.3 second, and a zone 3 protection may wait up to 1 second [8], [9].



▲**Figure 1. Distance protection relays: zone 1, zone 2, and zone 3.**

Hidden failures have been considered one of the main sources of large scale disturbances [3], [5], [15]. A hidden failure occurs when incorrect system states or control actions are triggered by another system event. It may induce widespread cascading failures such as the Northeastern blackout in 2003, which is initialized by a false relay trip [16]. Although solutions to hidden failures on traditional power systems have been extensively investigated [4], [7], [9], it is still extremely challenging to completely prevent such failures on large-scale complicated power systems.

The false trips of zone 3 relays are often associated with hidden failures [7], as shown in the past events. Such false trips have been identified among the main causes of blackouts (about 70% [3], [6]). In the meantime, zone 3 protection is also considered essential to power systems and we really rely on such protection in many cases [1], [2]. To deal with such false trips, new agent-based solutions have been proposed by utilizing smart grid communication networks [8], [9].

SG is in rapid development due to its salient features such as improving efficiency and reliability, better utilizing renewable energy, etc [10], [11], [17]–[19]. One key difference between the SG and the traditional power systems is that SG enables two-way power transmission with intelligent devices that exploit the rapid increase of computing power and the ubiquitous network communication systems. Many SG technologies have developed and many more new SG applications are still in development, e.g., Phasor Measurement Unit (PMU) technology [12].

Agent-based protection methods use a query-response model to avoid zone 3 false trips. A software agent is deployed at each relay. When a zone 3 relay r detects a remote disturbance from a line l, it will send a query to a master agent (MA) to verify if such a disturbance has been seen by other relays associated with the same transmission line. The MA then queries all related relays to pull their readings. After the MA receives all responses from these relays, it can determine if the disturbance on line l is a real fault or simply a temporary error. The MA sends a response to relay r to tell it how to react. Ideally, such

a solution can eliminate all over-sensitive tripping of zone 3 relays, assuming that there is only one transmission line error in the system and the query-response process can be completed before relay r is tripped based on its setting. However, the network delay requirement may be violated in real networks. Therefore, we have to consider practical network issues to further improve the reliability of zone 3 protection.

As we focus on the issues on SG communication network, the proposed solution in the following section will also help many other real-time SG applications depending on the same communication network.

3 Proposed Power-Aware Reliable Scheme

In this section, before we discuss the power-aware approach, we will first present an improved two-step network resource management scheme to ensure the message can be exchanged between a relay and its MA in time. We will first introduce the enhanced primary path construction in section 3.1, and present different backup methods in section 3.2 to further improve the communication reliability, in the case that the primary path fails due to unexpected network errors. Then, we will present a power-aware resource management frame-work to improve system reliability and resource management efficiency.

3.1 Enhanced Primary Path Selection with Reliability

To ensure a message is delivered on time between a MA and a relay, we first need deal with network delays for the agent-based protection scheme. Assume the MA is placed on a network topology based on certain criteria (which are out of scope of this paper). Our first task is to build a path for each remote protection relay to communicate with the MA. We name such a path as a Primary Path, and assume no links on this path fails. In our previous work, we proposed to use a shortest path based on the network topology as a primary path [14], which is more efficient in bandwidth use. In this paper, we further improve this process using the most reliable path, which emphasizes the path reliability. The shortest-path method minimizes the distance of a relay/bus to the MA so that a packet may have less resource requirement on each communication link; the most-reliable-path method minimizes the failure probability of a primary path by considering the reliability of its links.

Note that each bus may be associated with multiple relays. In general, only one relay at the bus will experience disturbances at a time and need to contact with the MA for guidance. So we usually only need one path from a bus to the MA.

As a single link failure is one of the most common cases in a network, the failure probability of a primary path is defined as:

$$P_f(path_i) = \sum_{j \in path_i} \left[P_f(link_j) \cdot \prod_{n \notin j} (1 - P_f(link_n)) \right] \quad (1)$$

where $path_i$ is a primary path from bus i to the MA, and $P_f(link_n)$ is the failure probability of link n. The enhanced primary path selection process is shown in **Algorithm 1**.

Algorithm 1 Primary path selection algorithm for buses

Input: Bus Set B, MA info, and Link Set L_c.
Output: A primary path for each bus.
Method:
1: **for** each bus $u_i \in B$ **do**
2: Find all path set P_{pr} from u_i to the MA
3: For each path in P_{pr}, assign its weight based on its path length (or path failure probability)
4: Select the path $path_{pr}(u_i)$ with the minimum weight as the primary path for u_i
5: **end for**

After finding a primary path for a remote relay, we need to determine its path delay requirement. The agent-based method has four main steps introducing delays: 1) A query is sent from a remote relay r to the MA, when it sees a temporary issue (e.g., a voltage surge or an impedance drop); 2) After the MA receives the query from r, the MA queries other related relays, where Rl is the set of relays { $r' : r' \in R_l$ and $r' \neq r$ }, where R_l is the set of relays protecting the same power line; 3) A response is sent from each r' to the MA; 4) the MA makes a decision based on the responses and sends its decision to r. The maximum allowable delay for a remote relay between sending a query and receiving a decision from MA can not exceed a given amount [8], [9]; otherwise, the relay will automatically trip a power line.

We determine the path delay requirement from a relay to the MA based on the following procedure. Denote the set of power transmission lines as L_p. For a power line $l \in L_p$, we find two relays r_1 and r_2 in R_l, which have the largest and the second-largest hop count h_{r1} and h_{r2} to the MA, respectively. The delay requirement of a remote relay is initialized to a default value D_0. (For ease of illustration, we assume that all remote relays have the same delay requirement. In real systems, the requirement of each relay may be different; we can represent them as $D_0(r_i)$ for relay r_i.) To ensure the delay requirement in the remote protection procedure, we proportionally divide the total delay requirement between these two relays: in case that one is the remote relay starting the query process and another is among the relays that respond to the MA. That is, the delay requirement between r_1 and the MA is set to $d_1 = h_{r1} \cdot D_0 / 2(h_{r1} + h_{r2})$; the $d$delay requirement between r_2 and the MA is set to $d_2 = h_{r2} \cdot D_0 / 2(h_{r1} + h_{r2})$. For other remote relays of l, their round trip delay requirements are set as no larger than d_2, because their path lengths to the MA are equal or smaller than the length from r_2 to the MA. There is no need to make the other relays to respond faster than r_1 and r_2. (As a relay may be used to protect multiple different lines, it may have different settings. In general, we use the minimal setting of a relay as its preset delay for remote protection.) The delay requirement of a relay is then equally divided along links of its

primary path and we then reserve resources on each link, as shown in **Algorithm 2**.

Algorithm 2 Primary path bandwidth reservation algorithm

Input: Remote Relay Set R, their Delay Assignment D_0 and Relay Inquiry Packet Size L_0.
Output: Primary Path Reservations on Link Set L_c.
Method:
1: **for** each relay $r \in R$ **do**
2: Equally divide its delay requirement $D_0(r)$ to links on its primary path $path_{pr}(r)$, i.e., assign delay on link i as $d(i)$
3: **for** each network link $l \in path_{pr}(r)$ **do**
4: Current reservation on link l is $b_{rsv}(l)$
5: Required capacity by r at l is $C_{pr}(l,r) = L_0/d(l)$
6: **if** $b_{rsv}(l) + C_{pr}(l,r) \leq C(l)$, where $C(l)$ is the total capacity of l **then**,
7: $b_{rsv}(l) = b_{rsv}(l) + C_{pr}(l,r)$;
8: **end if**
9: **end for**
10: **end for**

3.2 Enhancing Backup Path for More Reliability

Without network link failures, a primary path is able to handle the query process. However, in practical networks, links may fail. We need to deal with such failures for remote relay protection. As a single link failure is the most common case, we can handle it by using a backup path that is completely not overlapping with the primary path. However, there are several limitations in this scheme: 1) the network topology may not have another path that is a completely not overlapping with the primary path of some buses. 2) the length of a non-overlap backup path is often relatively long: for a fixed path delay, a longer path means a short delay and more bandwidth use at each link on the path, which is inefficient and may create unnecessary hot spots in the network. 3) a link on a non-overlap backup paths may not have enough capacity to support the backup requirement.

The first and the second limitation can only be fixed by changing network topology, which is out of scope of this paper. Here we focus on the third limitation and we propose to utilize power system information to select backup paths and manage resources more effectively. Assume we have historical data about a power network. Therefore, we know which power line carries more load and how likely it may fail, and we can assign a priority to each power line. Using such information, we can then decide how to allocate the limited network resources to maximize the system reliability. In this paper, we do not have such information available. We then use PowerWorld Simulator to generate such information as presented in the evaluation section.

Based on such known information of power systems, we use $P_f(S|line_i)$ to denote the probability that tripping a power line leads to a system failure in simulation. As such data give us the importance of power lines, we can prioritize them in protection. Assume there are N_l lines that may result in system failures. We equally divide the total system requirement P_f^S to these N_l lines. In this way, we expect the probability $P_f(S \cap line_i)$ does not exceed P_f^S / N_l for each of them. From (2)

$$P_f(S \cap line_i) = P_f(S|line_i) \cdot P_f(line_i) \tag{2}$$

we have:

$$P_f(line_i) = \frac{P_f(S \cap line_i)}{P_f(S|line_i)} \tag{3}$$

Consider that the failure of a line is usually due to the false trip of a relay at one of the two ends of the line. Then we can equally divide the requirement of $P_f(line_i)$ to the relays at two ends of the line. For a remote protection relay, when it sees a temporary issue, it sends an query to the MA and waits for the MA's response. If the query cannot reach the MA or the decision from the MA cannot be received by the relay within the required time, a false trip may happen. This case occurs if both a primary path and its backup path of a relay fail at the same time. Under the single link failure assumption, this only happens if the failed link is used by both path. We can define the probability as:

$$P^{relay\ false\ trip} = P_f^{the\ overlap\ links} = \sum_{j \in N_{ol}} [P_f(link_j) \cdot \prod_{n \neq j} (1 - P_f(link_n))] \tag{4}$$

where N_{ol} is the set of overlap links between the primary and backup path of the relay. Thus our goal is to find a backup path that has $P_f^{the\ overlap\ links}$ and can meet the minimum requirement of $P^{relay\ false\ trip}$. (Similar to finding a primary path, we find a backup path for a bus, instead for its relays.) The backup path selection procedure is presented in **Algorithm 3**. After a backup path is selected, resources are also reserved on the path, as shown in **Algorithm 4**. In case that a link does not have enough capacity to support all backup paths on it, the reservations are carried out with a specified order. For power

Algorithm 3 Backup path selection algorithm for buses

Input: Bus Set B and Communications Link Set L_c.
Output: Backup path for each bus.
Method:
1: **for** each bus $u_i \in B$ **do**
2: Find the smallest false trip probability $P_{\min}^{relay\ false\ trip}$ for relays on u_i
3: Calculate the minimum required failure probability for a backup path of u_i as:
4: **if** u_i does not have critical relays **then**
5: Set $P_{f,req}(u_i) = 1$
6: **else**

7: $P_{f,req}(u_i) = P_{\min}^{relay\ false\ trip}$
8: **end if**
9: Find all backup paths set P_{bp} to MA that are different from the primary path
10: Sort paths in p_{bp} based on hop count in an ascending order
11: Start from the first path in P_{bp}
12: **for** each backup path $p \in P_{bp}$ **do**
13: Compute the overlap link set N_{ol} between u_i 's primary path and p, then Calculate $P_f^{the\ overlap\ links}$
14: **if** $P_f^{the\ overlap\ links} \leqslant P_{f,req}(u_i)$ **then**
15: Select path p as the backup path
16: **end if**
17: **end for**
18: **end for**

Algorithm 4 Backup path bandwidth reservation algorithm for remote protection relays

Input: Zone-3 Relay Set R, their Delay Assignment D and Relay Inquiry Packet Size L_0.
Output: Backup path bandwidth reservations on Link Set L_c.
Method:
1: For each relay $r \in R$, find the powerline l_p it is located on and assign the probability $P_f(system|l_p)$ as the weight of relay r
2: Sort the set R using the weight assigned in the above step In a descending order
3: Start from the first relay in R
4: **for** each relay $r \in R$ **do**
5: Devide its delay requirement D on each link of its backup path $P_{bp}(r)$, for link i, its assigned delay is $d(i)$
6: **for** each network link $l \in P_{bp}(r)$ **do**
7: Current reservation on l is $b_{rsv}(l)$, total capacity of l is $C(l)$
8: Required capacity by relay r at link l is $C_{bp}(l,r) = L_0/d(l)$
9: **if** l is also used in the primary path of relay r **then**
10: Reservation of primary path on l is $C_{pr}(l,r)$
11: **if** $C_{pr}(l,r) \leqslant C_{bp}(l,r)$ **then**
12: $C_{bp}(l,r) = C_{bp}(l,r) - C_{pr}(l,r)$
13: **else**
14: $C_{bp}(l,r) = 0$
15: **end if**
16: **end if**
17: **if** $b_{rsv}(l) + C_{bp}(l,r) \leqslant C(l)$ **then**
18: $b_{rsv}(l) = b_{rsv}(l) + C_{bp}(l,r)$;
19: **end if**
20: **end for**
21: **end for**

lines that may blackout the system, their remote relays are "critical" and will be first considered. If a line is not expected to crash the system, we consider the consequence of tripping this line less important. The goal is to ensure that we can fulfill "critical" relays' requirement as much as possible.

Usually a bus contains more than one remote protection relays. We observe that many of the relays are used to protect different power lines. From this observation, we notice that it is possible to further reduce the required network resources, and we will discuss this issue in the evaluation section.

4 Peer-to-Peer (P2P) Protection Scheme for More Reliability

4.1 Motivation: MA is a Single Point of Failure

In the master-based relay protection, the MA receives a query from a substation relay and makes a decision based on system states whether the relay should trip or not, and then sends the decision back to the inquiry relay. Under normal network conditions, this mechanism works properly. However, as the MA is the only node responsible for making decisions, if it is shut down due to cyber-attacks or physical damages, the entire power system will lose the centralized protection, and relays may trip and cause unforeseen instability in the system.

As modern relays are powerful devices, we propose to use a P2P mechanism to deal with the potential unavailability of MA. The key observation is that a relay usually only need to check with a small group of related relays to protect a line. In this scheme, a relay at a substation communicates with other related relays about the state of local and remote power lines. With these responses, the relay can make a justified decision by itself whether to trip or not. An obvious advantage of this scheme is that the average response delay is much shorter than the master-based scheme, because a relay usually only asks other relays nearby, much closer than the MA. (This advantage may be elaborated when a relay need to make a very quick decision for special cases, even when the MA is still available.)

4.2 Proposed P2P Protection Procedure

Identify related relays and form a peer group. For each transmission line, we need first identify the set of related primary and remote relays for a power line and form a relay peer group for the line, shown in **Algorithm 5**.

Algorithm 5 Identify relay protection set for power lines

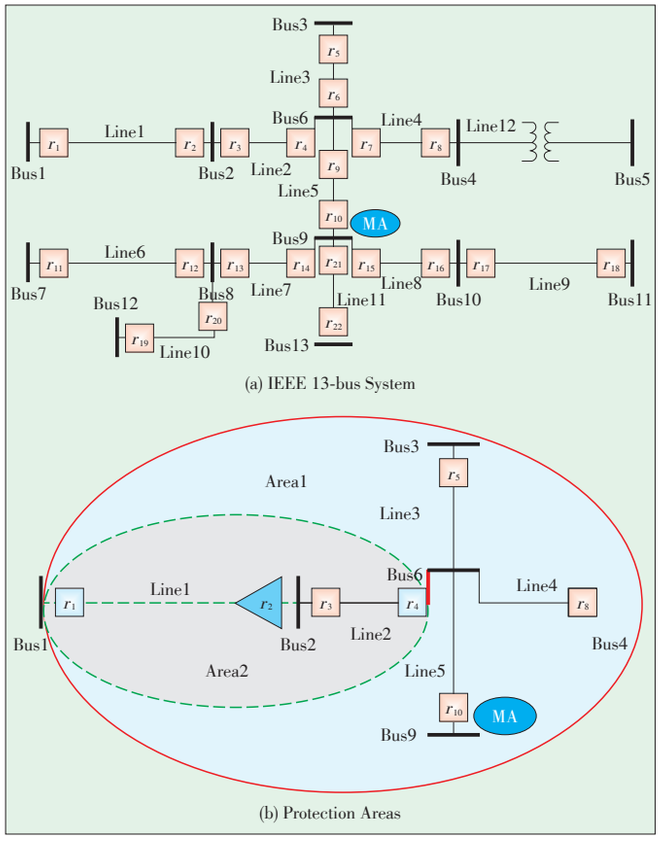
Input: Bus Set B, Power Line Set L_p and Relay Set R.
Output: Protection relays for each power line.
Method:
1: For each relay $r \in R$, we know which bus it is located and which line it serves as primary relay
2: **for** each power line $l_n \in L_p$ **do**

3: Assume the two buses at each end of l_n are u and v
4: For two relays r_u, r_v located at u, v and protect l_n, they are the primary relays of l_n
5: Identify all buses X that directly connected to u or v, while $u \notin X$ and $v \notin X$
6: **for** each bus $x' \notin X$ **do**
7: Denote the power line between (x', u) or (x',v) as l'_n
8: Identify the relay r_b that is located at x' and protects l'_n as primary relay, then r_b is the remote backup relay for line l_n
9: **end for**
10: **end for**

We give an example in **Fig. 2**, for $Line_2$, r_3 and r_4 are the primary relays and (r_1, r_5, r_8, r_{10}) are the remote protection relays. If any remote relay of this set sees a disturbance, it will check with one or more other relays within this set.

When the inquiry relay receives replies from other peers, it uses a voting scheme to decide the action.

For example, if relays with positive confirmations outnumber relays that do not see the fault, the inquiry relay will assume that there is a "real-fault" in the transmission line, and will trip the line when its primary relay fails to do so; otherwise, it assume no fault.



▲**Figure 2. The power system can be divided into different protection areas with the corresponding sets of relays.**

The primary path selection and resource reservation on each link of a path is shown in **Algorithm 6**. We have the following assumptions here. 1) A relay will communicate with all other related peers. 2) At one moment, there is only one hidden failure exposed [9], e.g., one relay has abnormal reading. Moreover, if there is only one hidden failure in the system, a single response from a peer is sufficient to make the decision. 3) At this step, the effect of link failure to the protection is not considered; and we will discuss backup schemes in the following. With the proposed P2P scheme, even if the master agent is shutdown unexpectedly, relays in the system are still able to make correct decisions to prevent the false trips of power lines.

Algorithm 6 Primary path selection and bandwidth reservation algorithm for P2P scheme

Input: Relay Zone 3 Delay Assignment D_0, Power Line Set L_p and Communications Link Set L_C.
Output: Bandwidth Reservations on Links L_C.
Method:
1: For each communication link $l \in L_c$, initialize reservation $b_{rsv}(l)$ to 0
2: **for** each power line $l_n \in L_P$ **do**
3: Find all zone-3 remote backup protection relays R_b and primary protection relays R_p
4: **for** each relay $r_i \in R_b$ **do**
5: **for** each relay $r_j \in (R_b \bigcap R_p)$ and $r_i \neq r_j$ **do**
6: **if** path is not set between r_i and r_j **then**
7: Find a shortest hop count path p from r_i to r_j, which is different from the primary path
8: Assume path p has H hops, then on each link l of p, the reservation of r_i is $Crsv(r_i,l) = \frac{L_0}{D_0/H}$ ▷ L_0 is the packet size
9: **for** each link $l \in p$ **do**
10: $C(l)$ is capacity of l
11: **if** $b_{rsv}(l) + C_{rsv}(r_i,l) \leqslant C(l)$ **then**
12: $b_{rsv}(l) = b_{rsv}(l) + C_{rsv}(r_i,l)$
13: **end if**
14: **end for**
15: **end if**
16: **end for**
17: **end for**
18: **end for**

In the P2P scheme, we have two types of delays: 1) the (maximum) delay to send a query to other related relays, and 2) the (maximum) delay for other relays to send their responses back to the inquiry relay. The round trip delay should not exceed a pre-defined time period D_0 to avoid false trips. To make sure the decision can be made within the required time period D_0,

we need to reserve network resources for a path from a relay to another relay. The relay delay requirement to and from a peer relay can be set to $D_0/2$. Assume the path consists of H hops and each inquiry has size L_0, the required resource on each link is $L_0/((D_0/2)/H)$.

As in the master-based scheme, the P2P scheme can also use backup paths to deal with communication link failures. Unlike the master-based scheme where the reservation is required between each bus and the master agent, in the P2P scheme, we can reduce the network usage by answering the following questions: 1) Does the P2P scheme need to backup for all of its primary paths between relays? 2) For the backup path used in the P2P scheme, whether to use overlapped or non-overlapped paths? For the first question, we consider that a minimum of two replies may be enough for the inquiry relay to make a majority decision, given the fact that two relays have hidden failures simultaneously is very low [9]. In addition, in [20], it is considered that, if the system is not in a "stressed state", which means the system is not close to unstable operational condition, a relay can even make decision without the responses from other relays. For the second question, due to the specific topology of a system, non-overlap paths can be much longer than the normal paths, especially for the P2P scheme in which primary paths are mostly just a few hops. As an alternative, overlapping backup paths may be used if we can still meet the system requirement. The advantage is obvious: overlapping paths are shorter, thus consume less network resources at each link. The backup path selection process and the resource reservation process are shown in **Algorithm 7** and **Algorithm 8**. Note that since some relays are protecting multiple lines, for example, r_i and r_j protect $line_k$ and $line_l$ simultaneously, then they can both be used as a backup protection relay pair for the two lines. In this way, when we protect $line_k$ with r_i and r_j, we only need to find one additional backup path for protecting linel, which save resources instead of using two different backup paths.

Algorithm 7 Backup path selection algorithm for P2P scheme

Input: Power Line Set L_p, Communication Link Set L_c and required backup path number N_u.
Output: Backup path between a relay and its peer relays.
Method:

Initially there is no backup path for any relay in the system
for each power line $l_n \in L_p$ **do**
  Find all zone-3 remote backup protection relays R_b and primary protection relays R_p
  For each relay, set the number of required backup peers as $N' = N_u$ ▷ For each relay, we hope it has backup paths to N_u peers
  for each relay $r_i \in R_b$ **do**
    Denote peer relays of r_i as $R'_i = (R_b \cap R_p) \not\ni r_i$
    Denote the current backup peers of r_i, whose backup paths already found, as R_x, its size is N_x
    if $N_x \geq N_u$ **then**
      Continue to next relay in R_b
    else
      We still need to find $N'_i = N_u - N_x$ number of backup peers
    end if
    for relay r_j in R_x **do**
      Exclude r_j from R'_i ▷ We already have backup path to r_j
    end for
    Find N'_i number of peers from R'_i, which have the shortest hop count paths as the backup peers of r_i ▷ The paths between each of the found relay and r_i should be different from their primary paths, they can have overlapped links with the primary paths or be totally non-overlapped
  end for
end for

Algorithm 8 Backup path bandwidth reservation algorithm for P2P scheme

Input: Relay Zone 3 Delay Assignment D_o, Power Line Set L_p, Communication Link Set L_c.
Output: Backup path reservation for each relay and its backup peers.
Method:

For each communication link $l \in L_c$, its reservation is $b_{rsv}(l)$
for each power $l_n \in L_p$ **do**
  Find all zone-3 remote backup protection relays R_b and primary protection relays R_p
  for each relay $r_i \in R_b$ **do**
    for each relay $r_j \in (R_b \cap R_p)$ and $r_i \neq r_j$ **do**
      if r_j is not a backup peer of r_i OR path between r_j and r_i is already reserved **then**
        Continue to next relay
      end if
      Denote the path from r_i to r_i as *path*
      Assume *path* has H hops, then on each link l of path, the reservation of r_i is $C_{bp,rsv}(r_i,l) = \frac{L_o}{D_o/H}$ ▷ L_o is the packet size
      for each link $l \in path$ **do**
        $C(l)$ is capacity of l
        if l is also used in the primary path of r_i and r_j **then**
          The primary path reservation on l is $C_{pr,rsv}(r_i,l)$
          $C_{bp,rsv}(r_i,l) = \max(C_{bp}, rsv(r_i,l)) -$

$C_{bp,rsv}(r_i,l),0)$
16: **end if**
17: **if** $b_{rsv}(l)+C_{bp,rsv}(r_i,l)\leqslant C(l)$ **then**
18: $b_{rsv}(l)=brsv(l)+C_{bp,rsv}(r_i,l)$
19: **end if**
20: **end for**
21: **end for**
22: **end for**
23: **end for**

We can compute the failure probability of a power system, $P_f(S)$, as shown in (5) to (7). We assume that the false trips of one critical line will result in a system failure, and there are different critical lines under different system load states. The total failure probability of the system is the sum of probability {*system fails and line$_i$ fails*}. Then, based on the known historical information of a power system, we use $P_f(S|line_i)$ to denote the conditional probability that tripping a power line leads to a system failure in simulation. With the above data given, the $P_f(S\bigcap line_i)$ will be determined by the probability that a power line is falsely tripped, denoted as $P_f(line_i)$. As we have mentioned before, the malfunction of zone 3 remote relay is a common reason for false trips. With the deployment of agent-based protection, under normal conditions, we can deal with such potential malfunctions. However, the failure still exists if either of the primary relays on a power line cannot obtain correct responses from the MA or other peers. Thus, the probability directly relates to the false trip probability of a relay, $P^{relay\ false\ trip}$, as in (7), where $relay_{i,1}$ and $relay_{i,2}$ are the two relays at each end of $line_i$ (assume each time only one relay is exposed to a hidden failure). We will see that different primary and backup paths selection will affect the false trip probability of a relay as shown in the evaluation section.

$$P_f(S)=\sum_{line_i\in S}P_f(S\bigcap line_i) \tag{5}$$

$$P_f(S\bigcap line_i)=P_f(S|line_i)\cdot P_f(line_i) \tag{6}$$

$$P_f(line_i)=P^{relay_i,1\,false\,trip}+P^{relay_i,2\,false\,trip} \tag{7}$$

5 Performance Evaluation

5.1 Evaluation System Setting

We evaluate the proposed schemes on the IEEE 39-bus system [9]. We simply assign the MA at bus 16 because the maximum hop count from bus 16 to other buses is the minimum among all buses, and it also has the highest connection degree in the system. (More sophisticated MA assignment schemes need detailed power system and communication network information, which is out of the scope of this paper.) For testing purposes, to make every bus have a non-overlap path for comparison, we modify the topology slightly by adding a communication link between bus 19 and bus 21. Assume bus 21 is the closest bus for bus 19. Assume all query and response packets have the same size of 80 bytes, e.g., a simple PMU packet. We set the system failure requirement to 10^{-5}, which is a higher requirement than current power grid [24], and set the communication link capacity to 1.5 Mbps (one T1 line) [25] with a failure probability no more than $P_f(link)=10^{-5}$ [26]. In this case, the probability of two or more links fail simultaneously is about 10^{-8}, which is much smaller than the system requirement. Thus, in this paper, we only consider a single link failure.

To build power system knowledge, we use the PowerWorld simulator [21] to obtain the conditional probability $P_f(S|line_i)$. As we know, more reactive loads cause more system losses, and result in various instability issues which may lead to system failures. We follow the methods used in [22], [23], and gradually increase the reactive loads of all PQ buses that have nonzero reactive loads, by setting $load_{new}=load_{base}\cdot(1+x)$. The increase step of x is 10% of the base load each time. At each system load setting, we examine system contingency by tripping power transmission lines one by one to check if the system fails (shown as a blackout in PowerWorld). We vary x in a range of (0; 3.3), because a blackout usually happens when $x\geqslant 3.4$, even if we do not trip any line. As a result, we have $P_f(S|line_i)=\sum_{k=0}^{3.3}P(x=k)\cdot I_{failure}(line_i)$, where $I_{failure}(line_i)$ equals to 1 if a system failure happens; otherwise, it is 0. For $line_i$ whose tripping may cause system failures, we obtain its $P_f(S|line_i)$ based on the above procedure, associated with 15 lines ranging from 0.8% to 4.2%. We use these data for optimizing backup path selection later.

5.2 Performance of Primary Selections and Backup Paths without/with Power Knowledge

To evaluate the two primary path schemes and corresponding backup path schemes, we assign the failure probability of a communication link according to the amount of transmitted power on the corresponding power line. (Assume each communication link connects the same buses as its power line.) For lines with more than 200 MW power (in 39-bus system, under normal condition, we have 17 lines with real power more than 200 MW, which is about 50% of all power lines), we set their corresponding links with $P_f(link)=10^{-6}$; otherwise, $P_f(link)=10^{-5}$. As shown in **Table 1**, when using primary paths only, neither primary selection scheme alone can achieve the system requirement (10^{-6}), as shown in the first row. The reliability-based primary-path selection does a little better than the shortest path selection. After adding backup paths, both schemes can fulfill the system requirement and achieve similar system reliability, as shown in the second row.

Using power knowledge can improve system reliability. As discussed in Section 3, we can handle a single link failure on a primary path by using a completely non-overlap backup path

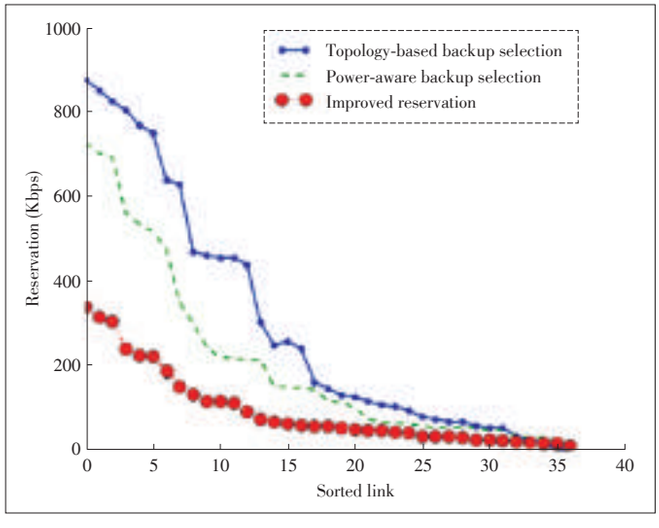
▼Table 1. Comparison of system reliability

Failure probability	Shortest hop count based	Reliability
Primary path only	1.58×10^{-6}	1.32×10^{-6}
With backup path	1.18×10^{-7}	1.22×10^{-7}

for each relay as a topology-based backup selection. However, this method consumes more resources. We utilize power system knowledge to address this issue. As mentioned before, we observe 15 lines that may lead to system failures under different load settings. Therefore, we prioritize these lines and their protection relays to better use network resources. Here we set $P_f(link)=10^{-5}$ for all links. Compared with using complete non-overlap backup paths, such a power-aware backup path selection significantly reduces the bandwidth reservation on almost every link, and the average bandwidth saving across all links is about 18%. The upper two curves in **Fig. 3** show the comparison of reservations on links. We sort them from high to low for easy illustration. In the above, we compare the maximum required link reservation on the 39-bus system for using non-overlap backup paths and partially overlapped backup paths with the system failure requirement $RS=10^{-6}$. To further show how the proposed power aware scheme can reduce link reservations, we also test it with system failure requirement $RS=10^{-5}$.

Assume the single link fails with $P_f(link)=10^{-5}$. As shown in **Table 2**, compared with the non-overlap path scheme, the power-aware scheme can significantly reduce bandwidth reservation (29% less) while still meeting the system reliability requirement. In the second row, we set the value of non-overlap path scheme as the "base" of 100%.

When some links do not have enough capacity, we assign higher priorities to the protection relays of important lines based on the power knowledge to further improve the system reliability. We compare three simple resource reservation orders in the following. The first order is to start to allocate bandwidth from the most important relay to least important one; the second order use the opposite order for comparison; the third order is to allocate bandwidth using random bus orders (here we compute the average of 20 random orders). To show the case that some relays may not obtain the required bandwidth on a link, we make link 19 as the bottleneck and reduce its capacity from 1.5 Mbps to 550 Kbps. We set the system requirement as 10^{-6}, and the failure probability of links as 10^{-5}. We observed that the relays without enough reservation vary in the different orders. For the latter two orders, some relays do not obtain enough bandwidth for their paths, for example, relays protecting Line {3, 5, 6, 15, 19, 21, 31}. However, these lines have higher probabilities in causing system failures if improperly tripped. The system failure probabilities for different orders are 1×10^{-7}, 1.5×10^{-6}, and 6.7×10^{-7} respectively.



▲Figure 3. Backup path selection with/without power knowledge and improved reservation scheme.

▼Table 2. Comparison of maximum link reservation for different backup path schemes and requirements

	Topology-only $R_s=10^{-6}$	Power-aware $R_s=10^{-6}$	Power-aware $R_s=10^{-5}$
Max reservation	878	725	625
Percentage(%)	100	82	71
Failure probability	0	1.0×10^{-7}	5.7×10^{-7}

Smart Reservation. A bus may have multiple remote relays for protecting different power lines. In common cases, they will not simultaneously communicate with the MA. This provides us another opportunity to further reduce the required bandwidth on communication links. Assume only one relay experiences a hidden failure or only one power line has disturbances. For example, in the IEEE 39-bus system, only bus 26, 28, and 29 have two remote relays protecting the same line; remote relays on other buses all protect different power lines. In this case, we only need to reserve bandwidth for relay r_i with the most strict delay requirement on a bus. Because other relays on that bus do not have delay requirement as high as r_i, the reserved capacity is sufficient for them to communicate with the MA. Again, we set the system requirement as 10^{-6} and $P_f(link)=10^{-5}$. The maximum required capacity on a link decreases from 725 Kbps to 366 Kbps, a nearly 50% saving. As shown in Fig. 3, comparing the lower two curves, on average, we save about 39% capacity on each communication link. The overall system failure probability is 1×10^{-7}, still meeting the system reliability requirement.

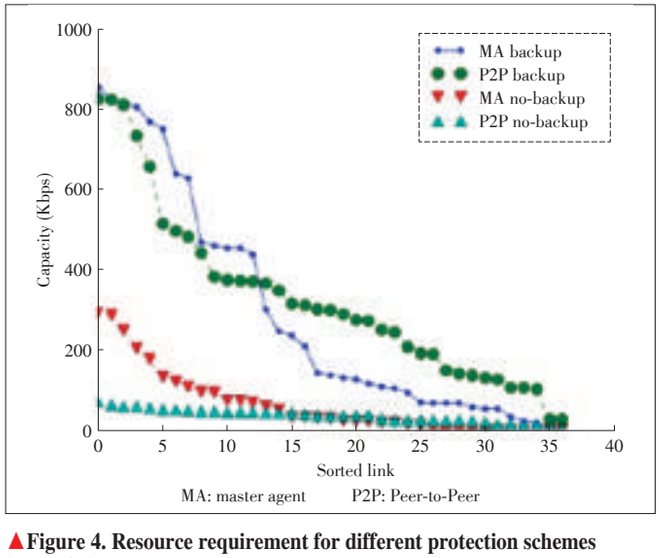
5.3 Comparing Master-Agent-Based and P2P Schemes

We follow the method in [9], assume at a single moment, there is only one hidden failure exposed in the system: a disturbance is applied to a power line that the relay with a hidden failure will sense the disturbance, and the communication network has a single link failure at most. We compare the resource requirement for the protection and the false trip proba-

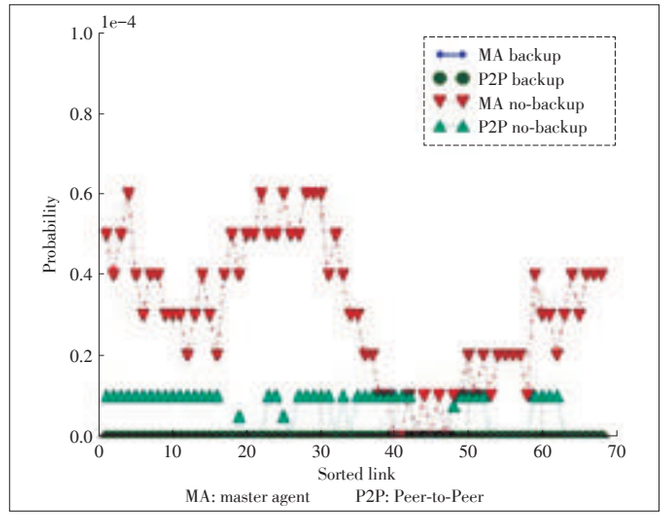
bility of each relay, under four schemes: the MA scheme without backup paths, the P2P scheme without backup paths, the MA scheme with backup paths, and the P2P with backup paths. For the primary path selection, both the MA scheme and the P2P scheme use the shortest path to the master node or peers. For the backup path selection, both schemes use non-overlap backup paths.

The result for resource requirement is shown in **Fig. 4**. Without backup paths, the P2P scheme consumes the minimum resources since the distance to peers are shorter than in the MA scheme. However, adding backup paths to both schemes significantly increases the resource usage. **Fig. 5** shows the false trip probability of each relay in the system. Under the single link failure condition, in the MA scheme without backup paths, if the primary path of a relay fails, it cannot communicate with the MA and will result in a false trip. As we can see, more relays in the MA scheme are affected than in the P2P scheme, For the P2P scheme, since each peer can send its response to the inquiry relay, the false trip occurs if all paths to the relay's peers fail, which means the failed link is shared by all paths to the peers. Intuitively, this probability is much lower than the failure of a primary path in the MA scheme. With non-overlap backup paths, both the MA scheme and the P2P scheme can handle a single link failure, in which all relays have zero failure probability. Combining the relay false trip probability with the power data $(P_f(S|line_i))$, the system failure probability can be computed.

Without backup paths, the system reliability $P_f(S)$ in the P2P scheme is 0.55×10^{-6}, which is about 4-time better than that of the MA scheme (2.62×10^{-6}). Note that the P2P scheme can meet the 10^{-6} requirement but the MA scheme cannot. This matches the results from Fig. 5 that the failure of a primary path of a relay has more influence in the MA scheme, because all relays must first contact the MA and then receive a decision from the MA. While we can protect relays from false trips using non-overlap backup paths, judging from the resource requirement from Fig. 4, the cost of non-overlap backup path in the two schemes do not have much difference. The potential difference between the two is the response delay.



▲**Figure 4. Resource requirement for different protection schemes with/without backup path.**



▲**Figure 5. False trip probability of each relay, assume a single link failure.**

The response delay counts from the time when the query is sent until a decision reaches the inquiry relay. This delay is closely related to the path distance (hop count), especially when the traffic load is light most of the time. We compute the maximum, minimum and average hop counts for both the MA scheme and the P2P scheme. For the MA scheme, the primary/backup path distance is between a bus and the MA bus. The result for the MA scheme with non-overlap backup paths is shown in Table. 3. As a comparison, the result of the P2P scheme with non-overlap backup paths is also given. In the P2P scheme, paths exist between each pair of "corresponding relays". Note that in both the MA and P2P schemes, the minimum hop count is 0. The reason is that, in the MA scheme, there are a few relays locating at the same bus with the MA; for the P2P scheme, in the 39-bus system, relays (64,67) and relays (66,68) are located at bus 28 and 29, respectively, and they are protecting the same lines. Thus the communication between these relays are within a substation. (We assume the indexes of relays for a power transmission line with index i are $2\cdot i$ and $2\cdot i-1$.). In addition, although the average path length between (the MA and a non-MA bus) or (P2P peers) are similar, in the MA scheme the query process takes two round-trip delays. While in the P2P scheme, there is only one round-trip delay (as shown in the "Actual" column of **Table 3**). As link loads are not heavy most of the time, a shorter path benefits the protection with faster response delays.

Compare the effect of full backup vs. partial backup paths and the effect of overlap backup vs. non-overlap backup paths. The above case is the worst case resource requirement for the

▼Table 3. Path hop count in the MA scheme

	Max	Min	Average	Actual
MA primary path	6	0	3.2	6.4
MA backup path	10	0	6.2	12.4
P2P primary path	3	0	2.0	2.0
P2P backup path	12	0	5.7	5.7

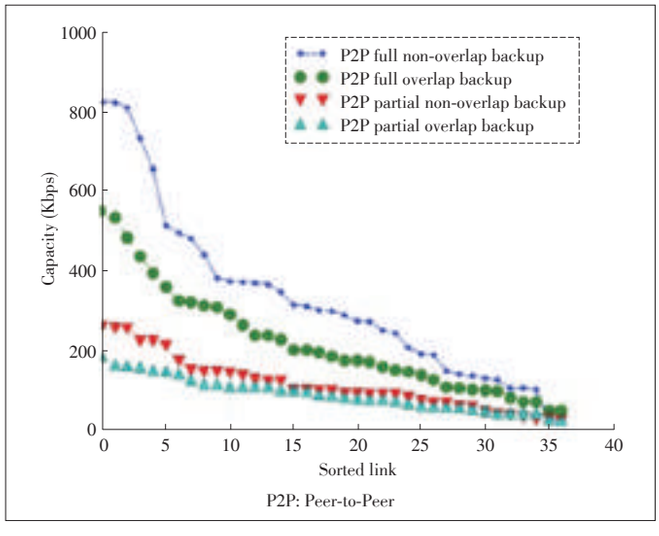
P2P scheme since a non-overlap path between each pair of "corresponding relays" are reserved. As a comparison, the shortest-hop-count overlap backup path is tested in the P2P scheme. Similar to the non-overlap scheme, resources for each "corresponding relay pair" is reserved as well. We exam the "stressed case" and assume two replies returning from peers will enable the inquiry relay to make correct decision.

Fig. 6 shows network resource requirements for each protection scheme.

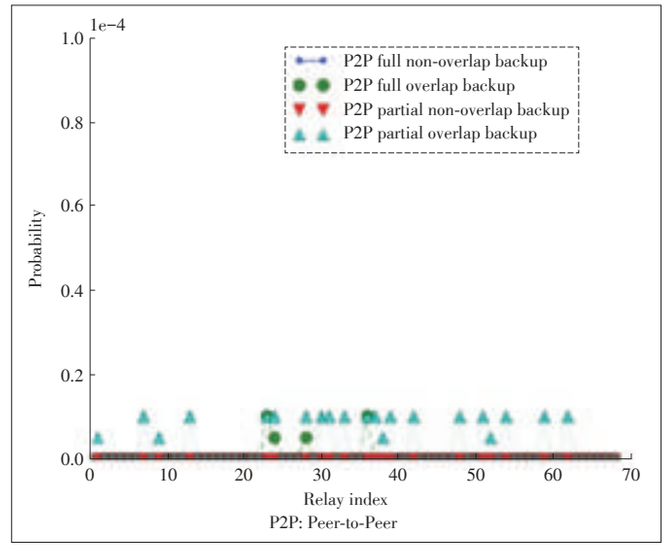
Fig. 7 shows the false trip probability of relays. We see that only four out of about 68 relays are affected when using overlapping paths. Fig. 6 and Fig. 7 also show that the resource requirement further decreases because now each relay only reserves for two backup paths.

When using non-overlap backup paths, all relays can handle the single link failure; while using overlapping backup path uses less resources at the cost of a few more potential false trips. **Table 4** shows how the total resource requirement and the changes of system reliability for different backup schemes.

Compare the effect of the number of overlapping backup paths in the P2P scheme. We try to identify how many overlapping backup paths should be used in the P2P scheme by varying the number of backup paths for each relay from two to five. We choose the shortest hop count path as a backup path, and allow this path to have overlapping links with its primary P2P path. The results are summarized in **Table. 5**, including the total resource requirement, the overall failure probability of the system, number of potential relay failure, and average relay failure probability. As we can see, the more backup path we use, the less number of relays that will have false trips. The resource requirement is as expected: the more backup paths we use, the more resources we consume. Comparing the first two lines of Table 5, a significant point is that, when we increase the number of overlap backup paths from two to five, the resource cost doubles, but the reliability is improved by ten-folds. While the trends of improvement are different in in the second and forth lines, the reason is that power lines are not of the same importance: for some lines, the false trip may lead to severe system failure, while others are not.



▲Figure 6. Resource requirement for P2P schemes with/without backup path for each relay.



▲Figure 7. Relay false trip probability for P2P schemes with/without backup path for each relay, assume a single link failure.

▼Table 4. Total resource requirement and system failure probability with/without backup path for each relay

	Full non-overlap	Full overlap	Two BP non-overlap	Two BP overlap
Resource	12140	8140	4131	3372
$P_f(S)(\times 10^{-7})$	0	0.2	0	2.76

6 Conclusions and Future Work

In this paper, we have developed more reliable remote relay protection schemes by exploring both network link reliability and power systems knowledge on SG. Furthermore, to address the single point of failure of common centralized control center, we have also investigated P2P protection approaches. The simulation results show that the proposed method can significantly improve power system reliability while utilizing network resource more effectively.

In this paper, as most existing research, we assume that a

Table 5. Total resource requirement, System failure probability, and Number of potential failure relay and their average failure probability under different P2P schemes

	2 Overlap backup	3 Overlap backup	4 Overlap backup	5 Overlap backup
Resource(Kbps)	3372	5122	6646	7638
$P_f(S)(\times 10^{-7})$	2.76	2.5	1.0	0.29
Number	21	16	9	6
$\overline{P_f(relay)}(\times 10^{-6})$	2.8	2.2	1.2	0.6
$\frac{Normalized}{P_f(realy)}$	4.67	3.67	2	1

cascading failure starts at a single line, which leads to the sequential trips of neighbor lines. However, recent research [27] demonstrated that this sequence is not easily characterized and may be geographically separated, i.e., the cascading does not necessarily develop in a contiguous manner. Our future investigation will focus on this new direction. Although the agent-based scheme is helpful in preventing the cascading failure, we notice that it also has the potential to mitigate the damage of already on-going cascading, e.g., by tripping certain lines in advance. The foundation of such schemes is reliable real-time network communications, from collecting system states to accurate transmission of decisions to each critical location.

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